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An evaluation of fishery and research data collected during the Phase 1 sea cucumber fishery in British Columbia, 1998 to 2007

Évaluation des données de recherche et sur la pêche recueillies lors du stade 1 de développement de la pêche des holothuries du Pacifique en Colombie-Britannique, de 1998 à 2007

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Abstract

Investigations have been underway since 1998 to fill some of the knowledge gaps in the giant red sea cucumber fishery that were originally identified in 1996. The current regime of annual harvest conducted in only 25% of the British Columbia coast, along with experimental fishing, have allowed a thorough study of the effects of harvesting on the density and size of sea cucumbers.

Surveys were conducted in six commercially-open harvesting areas; all had a decline in density ranging from 10% to 23% between 1998 and 2007. There was a decline in the mean weight of sea cucumbers in four of the six open areas ranging from 12% to 17%.

Four experimental fishery areas (EFAs) were developed to study the effects of various harvest levels on density and sea cucumber size. Five sites (no harvest, 2%, 4%, 8%, and 16% harvest rate) were established in each EFA and were harvested annually, based on virgin population estimated at the beginning of the study. The sites with higher harvest rates, 8% and 16%, showed large decreases in density between the first and last year of study. Lower harvest rates (control, 2% and 4%) did not show the same levels of decline. The mean weight of sea cucumbers also declined during this time period, significantly in approximately half of the 20 EFA sites and by up to 37%. The declines in mean split weight were not entirely the result of harvesting levels, as size also declined in control sites.

A latent productivity model was used to estimate the maximum sustainable harvest rate, using the 10 years of data from the experimental fishery areas. Maximum sustainable harvest rates, at the 1 percentile level (i.e. 99% confident that the true harvest rate is higher), ranged between 3.5% and 10.3% of estimated virgin biomass over the four EFAs. In no EFA was the 16% harvest rate found to be sustainable.

A total of 7.7% of the shoreline available for fishing was targeted by harvesters in 2005. The fleet does not target the same pieces of shoreline repeatedly and they appear to harvest different areas from year to year. As was expected, the amount of shoreline targeted by harvesters increased with quota levels, but natural reserves with high densities of sea cucumbers persisted.

Results from these Phase-1 fishery investigations form the basis of recommendations to resource managers to expand the sea cucumber fishery to other areas of the BC coast using a conservative annual harvest rate ranging from 3.5% to 10.3% of virgin biomass. A limit reference point (LRP) of 50% virgin biomass is recommended, and an upper stock reference point (USR) of 60% to 80% virgin biomass is suggested. It is further recommended that the experimental fisheries be continued as they are a valuable tool for monitoring population response to fishing, and that no-harvest reserves be established in fishing areas for comparative monitoring.

Résumé

Des études sont en cours depuis 1998 dans le but de combler certaines lacunes sur le plan des connaissances relatives à la pêche des holothuries, identifiées pour une première fois en 1996. La récolte annuelle en vigueur autorisant la pêche dans seulement 25 p. 100 des secteurs du littoral de la côte de la Colombie-Britannique, en plus des pêches expérimentales, ont permis de réaliser une étude exhaustive sur les effets de la récolte sur la densité et la taille des holothuries.

Des relevés ont été effectués dans six secteurs d'exploitation ouverts à la pêche commerciale; tous les relevés ont indiqué une baisse de la densité de l'ordre de 10 à 23 p. 100 entre 1998 et 2007. On observe également une diminution du poids moyen des holothuries dans quatre des six secteurs ouverts, oscillant entre 12 et 17 p. 100.

Quatre zones de pêches expérimentales (ZPE) ont été mises en place afin d'étudier les effets des divers taux d'exploitation sur la densité et la taille des holothuries. Cinq sites (taux d'exploitation de 0 %, 2 %, 4 %, 8 % et 16 %) ont été établis dans chacune des ZPE et des récoltes y ont été faites chaque année, en fonction de la population vierge estimée au début de l'étude. Les sites présentant des taux d'exploitation plus élevés, 8 et 16 p. 100, ont révélé de plus fortes baisses de la densité entre la première et la dernière année de l'étude. Les taux d'exploitation plus bas (taux de contrôle de 0 %, 2 % et 4 %) n'ont pas révélé les mêmes niveaux de diminution. Le poids moyen des holothuries affichait également une baisse au cours de cette période de façon significative dans environ la moitié des 20 zones de pêches expérimentales et jusqu'à 37 p. 100. La diminution du poids éviscéré moyen ne peut être attribuée totalement aux taux d'exploitation, puisque la taille a également diminué dans les sites de contrôle.

Un modèle de productivité latente a été utilisé afin d'estimer le taux d'exploitation durable maximal, à partir des données recueillies sur dix ans dans les zones de pêches expérimentales. Les taux d'exploitation durable maximaux, au 1er percentile (c.-à-d., sûr à 99 % que le taux d'exploitation réel est plus élevé), oscillaient entre 3,5 et 10,3 p. 100 de la biomasse vierge estimée dans les quatre ZPE. Le taux d'exploitation de 16 p. 100 n'a été jugé durable pour aucune des ZPE.

Un total de 7,7 p. 100 du littoral disponible pour la pêche a été ciblé par les pêcheurs en 2005. La flotte ne cible pas les mêmes secteurs de littoral à répétition et semble pêcher dans des secteurs différents d'année en année. Comme nous l'avions prévu, la portion du littoral ciblée par les pêcheurs a augmenté avec les quotas, mais les réserves naturelles affichant de fortes densités d'holothuries ont persistées.

Les résultats de ces études du stade 1 de développement des pêches forment la base des recommandations formulées à l'intention des gestionnaires de la ressource en vue d'étendre la pêche des holothuries à d'autres zones de la côte de la Colombie-Britannique en appliquant un taux d'exploitation annuel conservateur oscillant entre 3,5 et 10,3 p. 100 de la biomasse vierge. Un point de référence limite (PRL) de 50 p. 100 de la biomasse vierge est recommandé, et un point de référence supérieur (PRS) du stock de 60 à 80 p. 100 de la biomasse vierge est suggéré. Il est également recommandé que les pêches expérimentales se poursuivent puisqu'elles sont un outil précieux pour la gestion de la réaction de la population à la pêche, et que des réserves de contrôle (sans capture) soient établies dans les zones de pêche aux fins de surveillance comparative.

1 Introduction

The fishery for the giant red sea cucumber (*Parastichopus californicus)* has been underway since 1971. Initially, it followed the 'boom and bust' pattern that is typical of most new fisheries where little is known of the population dynamics. Subsequently, the fishery underwent a series of arbitrary quota reductions, effort limitations and licence changes, described in Hand and Rogers 1999 and summarized in Table 1.

One of the challenges of assessing and managing a sea cucumber fishery is the paucity of life-history data and gaps in the knowledge of their biology and ecology. In particular, no practical method has been discovered to age the animals, which limits the use of models based on life-history. Rates of recruitment, growth and mortality are unknown. These soft bodied organisms are difficult to size, as they can easily change their body dimensions by absorbing/expelling water and contracting muscles in their body walls. In addition, their body weight changes seasonally, as they reabsorb their viscera and cease feeding during the winter months (Fankboner and Cameron 1985). Natural differences in the weight distribution between populations that inhabit different habitats further complicate matters, such that no proxy to age is available. Furthermore, juveniles are rarely observed in the course of surveying populations, being either cryptic or inhabiting nursery grounds elsewhere, leading to a major gap in knowledge of recruitment strength and the source of larvae.

In keeping with the Phased Approach for new and developing fisheries (Perry et al. 1999), a review of BC and Alaska sea cucumber fishery data and of all known biological information was conducted in 1995 (Phillips and Boutillier 1998). Knowledge gaps were identified and recommendations were made to address them. In 1996, Boutillier et al. (1998) concluded that the fishery on giant red sea cucumbers in British Columbia was not providing the necessary information to allow assessment and evaluation of the impacts of the fishery on these stocks and recommended that the fishery be conducted in a manner that would provide the necessary data. Following these reviews, the Shellfish PSARC Subcommittee endorsed the recommendation to restrict the fishery to approximately 25% of the coast, in static areas, in order to provide an annual time-series of fishery data and fishing patterns in the commercial fishery.

The commercial fishery quota was initially based on a conservative population density estimates of 2.5 cucumbers per meter of shoreline, extrapolated from surveys conducted in Alaska (Larson et al. 1995), and a conservative annual harvest rate of 4.2% from analyses conducted in Washington State (Alex Bradbury, Washington Department of Fish and Game, unpublished document). An annual fishery, as opposed to a rotational fishery, would allow an evaluation of the nature and performance of fisheries and produce the required information on fishery impact in a timely manner. Locations within these open areas were surveyed to provide a time-series of abundance and allow an evaluation of fishery effects.

The Subcommittee also approved the use of select portions of the remainder of the coast, up to 25% of total BC shoreline length, for research. These were used to conduct

experimental fisheries that were designed to evaluate the response of exploited populations to different exploitation rates. Meanwhile, the majority of the coast was closed to harvest until knowledge from the annual commercial fishery and fishery experiments was sufficient to establish a precautionary and sustainable fishery coastwide.

In recent years, commercial fishermen have been reporting that annual harvest is leading to a reduced animal size in some sea cucumber populations, with resulting marketing problems. The industry requested that alternate areas be opened and made available under the quota fishery to reduce the effort that is concentrated in some areas of the BC coast and allow recovery of the populations. Industry also requested a return to a rotational harvest strategy for sea cucumbers over the entire BC coast. These requests prompted preliminary analysis of the accumulated biological data collected and the development of a computer model to evaluate the performance of a rotational harvest strategy. Results of this work were presented to PSARC in 2005 (Humble et al. 2007).

The initial estimated time-frame for data collection in the Phase 1 sea cucumber fishery was 10 years, which is five years after the first four-year old recruits entered the fishery. As of 2007, ten years have elapsed since the initiation of the adaptive management regime in 1997 and it was felt that enough experimental fishery data, annual commercial fishery data, survey and biological data had been collected to warrant a thorough evaluation. Accordingly, fishery managers submitted a Request for Working Paper (Appendix 1), with the stated objective to review and evaluate the fishery-dependent and fishery-independent data collected during Phase 1 of the fishery, discuss implications to stock sustainability and make recommendations for changes to the assessment framework. This paper specifically addresses the question of impacts of the commercial fishery, the spatial distribution of fishing effort, sustainable harvest rates and what an effective monitoring program for an expanded fishery would look like.

An overview of completed surveys, biosamples and experimental harvesting is presented. The effect of commercial harvesting, at the current conservative level, is evaluated as a time series of density surveys. Changes in density estimates in the experimental fishing areas, where different harvesting regimes were tested, are discussed. The changes in mean weight and weight distribution, in both commercially-open and experimental areas, is presented. The results of a latent productivity population model, which uses survey data from the experimental fishing areas, is presented; this includes posterior distributions of maximum sustainable harvest rates and population projections at different harvest rates. A geographical analysis of the harvesting patterns seen in the annual fishery is also presented. Finally, the discussion of this ten-year research program concludes with recommendations regarding the future of the sea cucumber fishery and requirements for continued monitoring and data gathering.

1 Changes in Population Density in Commercial Fishery Areas

1.1 Background

Since 1998, dive surveys of sea cucumber populations have been conducted in six separate commercial fishery areas (hereafter termed 'open surveys') (Figure 1). Field operations were funded by the Pacific Sea Cucumber Harvesters Association (PSCHA) and conducted by commercial divers aboard licenced fishing vessels, with a Fisheries and Oceans (DFO) biologist on board for all surveys. There was also participation from First Nations in survey areas where there was interest in the research.

In these surveyed areas, new biomass estimates based on the bootstrapped lower 90% confidence bound on mean density were used to adjust the quotas, thus leading to quota increases (or decreases) over time. A baseline density estimate of 2.5 sea cucumbers per metre of shoreline (c/m-sh) was initially used to calculate quotas for unsurveyed areas (Boutillier et al. 1998). In 2003, the baseline density was revised to 5.08 c/m-sh, based on all open survey results to that date (Campagna and Hand, 2004). For areas of the coast that are known to be less hospitable to sea cucumbers, or were suspected of having been over harvested in the past, the original 2.5 c/m-sh value remained in place.

Aside from the direct application of survey data for estimating biomass, survey results also provide a time-series of density estimates in commercially-harvested areas which allows an evaluation of the effect of harvest on sea cucumber abundance and distribution.

1.2 Data Description

1.2.1 Survey and Harvest History

Open surveys were repeated every four years (Table 2). All open survey areas had been harvested prior to the first survey being conducted and, therefore, do not represent virgin populations. Table 3 summarizes annual landings from these areas from 1985 to 2006, with the landings for the four years prior to the survey shown in bold.

1.2.2 Description of Survey Locations

The survey sites are located within the 25% of coastline open to commercial harvest over a range of geographical areas and habitat types (Figure 1). Sites were largely selected by the licence holders, given the understanding that quotas would be adjusted with survey results, and because densities were thought to be substantially higher than the conservative baseline estimate. The survey areas were also popular fishing spots that could be viewed as providing a response in a typically targeted area. A chosen survey area usually included approximately 400 km of shoreline length. All six locations add up to 30% of the shoreline that is open to commercial harvest. The survey areas were defined by the overall perimeter of several Pacific Fisheries Management Area (PFMA) Subareas grouped together. Although PFMAs have no logical application to sea cucumber stocks, they were convenient to use because they have geo-referenced boundaries and known shoreline measurements.

Surveys were conducted in May, June and July and repeat surveys were conducted the same month as the original survey. Two locations have been surveyed three times since 1998 (Gil/Gribbell and Area 7) and four have been surveyed twice (Trutch, Fitz Hugh Sound, Area 12 and Tofino).

Gil and Gribbell Islands: 1999, 2003, 2007

Located in the North Coast of BC and comprised of Subareas 6-3, 6-5, 6-6, 6-7, 6-27 and 6-28 (Figure 2). This area includes channel, island and inlet habitat and the topography is mainly of moderate to steep slopes and hard substrate. Tidal current flow ranges from low to very strong, while exposure to ocean swell varies from nil to moderate. The most common substrates were shell, boulder and bedrock. A diverse species composition of algal cover was found in current swept areas.

Trutch Island: 2001, 2005

Located in the North Coast of BC, this area lies in the Estevan Group archipelago (Figure 3) and comprises only Subarea 6-9. The exposure to wave action ranges from very low to very high and the current regime ranges from very low to very strong. The most common substrates were sand, boulder and bedrock. The algal cover consisted predominantly of *Agarum spp.*, *Nereocystis spp.* and *Macrocystis spp.*

Area 7: 1998, 2002, 2006

The area is located in the Central Coast of BC and includes Subareas 7-15, 7-17 and 7-30 (Figure 4). The topography is quite varied, with vertical to gentle slopes and substrate ranging from bedrock to mud. Conditions are typical of channels and inlets: moderate slopes of boulders with sand, shell and cobble. The exposure to wave action varies from nil to low, while the current regime ranges from nil to strong. Algal cover consisted mainly of *Agarum spp.*

Fitz Hugh Sound: 2002, 2006

Located in the Central Coast of BC, this area includes Subareas 8-3, 8-4, 8-5, 8-6 and 8-16 (Figure 5). It is characterized by large passages, inlets and islands, with exposure and current regimes ranging from low to moderate, slope ranging from vertical to flat and substrates commonly sand and bedrock.

Area 12 inlets: 2000, 2004

The area is located in the Broughton Island Group on the mainland shore of Queen Charlotte Strait, in the South Coast of BC and includes Subareas 12-40 and 12-41 (Figure 6). It consists of numerous shallow inlets and passages. The slope is moderate to gentle, the current is nil to extreme and the exposure to wave action is low. The substrate is primarily sand, shell or silt. The algal cover is mainly *Agarum spp.*

Area 24 Tofino: 2001, 2005

Located on the West Coast of Vancouver Island, the study area includes Subareas 24-04 through 24-10 and 24-14 (Figure 7). Topography is wide ranging, including inlets, bays, passages and open coastline. Exposure to wave action ranges from low to extreme and tidal current ranges from low to very strong. Exposed areas were characterized by sandy substrates against a rocky shoreline with gentle slopes between 20 and 40 feet.

1.3 Field and Analytical Methods

1.3.1 Field Methods

A random sampling design was used to estimate the density of sea cucumbers. Survey areas encompass approximately 400 km of shoreline each, in which a total of approximately 200 transects locations were randomly selected. This sampling intensity was expected to achieve a precision for the mean density estimate of ±15% at $\alpha = 0.10$ confidence level. Details of this experimental design are described in Campagna and Hand (2004).

Methods for determining the location of transects within the survey area have evolved over the years with the advent of new software and techniques (Campagna and Hand 2004). Ultimately, random transect location assignment was accomplished in GIS using an ArcView script. Transect locations were transferred from the ArcView map to hardcopy charts by matching land features or, as technology developed, plotted in Nobeltec software using land features. The locations of transects in the field were determined by matching the topography, bathymetry and landscape with chart features and utilizing global positioning systems (GPS). Coordinates of transect locations were recorded during field work, using the GPS equipment onboard. The same transect locations were re-surveyed in subsequent years.

At each transect location, surveys were conducted by SCUBA divers to a maximum depth of 60 feet gauge depth. Sea cucumbers are known to occur in deeper water, as observed on ROV and submersible footage (L. Yamanaka, pers. comm.), and approximately 6% of commercial harvest events take place deeper than 60 feet. However, a depth limit of 60 feet was selected as a good balance between safe diving practices and coverage of the fishable population. Estimates of population size from surveys are therefore conservative. Counts of sea cucumbers were recorded by the divers within a 4m wide swath, perpendicular to the shoreline, at 5m intervals. Habitat data including the dominant substrate and algae, together with depth, were also recorded at 5 m intervals. Full details are documented in Campagna and Hand (2004). Data are archived in the sea cucumber biological database and maintained by the Shellfish Data Unit at the Pacific Biological Station.

1.3.2 Analytical Methods

Transect survey data for each of the six commercial fishery areas were analyzed as a whole and separately by harvested and unharvested areas. Two criteria were used to define whether transects were in harvested areas. Firstly, transects were considered to be in a harvested area if a fishing event occurred within a 400 m buffer of the surveyed transect in the year previous to surveying. The 400 m buffer corresponds to the distance that a sea cucumber could travel in approximately 100 days (da Silva et al. 1986, Cieciel 2005). In the second criteria, transects were assigned to the 'harvested' category if a harvest event occurred within 400 m of the surveyed transect in at least three of the previous five seasons.

1.3.2.1 Density estimation

Transect-density was calculated as the number of sea cucumbers observed in a transect, divided by the size of the transect. Density is calculated and expressed in two different units; linear density (number of sea cucumbers per metre of shoreline) and spatial density (number of sea cucumbers per square metre). Linear density is the density estimate used in quota calculations for the fishing industry because no estimates of sea cucumber 'bed' area exist (whereas lengths of shoreline are known). For linear density the size of every transect is four metres wide. For spatial density, the transect size is length of the transect (in metres) multiplied by the width (four metres). The differences between the two forms of density can be quite large. For example, if transect A was 100m long with 50 sea cucumbers observed, it would have a linear density of 50 / 4m of shoreline = 12.5 c/m-sh and a spatial density of 50 / (100 m long x 4m wide) = 0.125 c/m^2. When this transect is compared to transect B, which also had 50 sea cucumbers but is only 25m in length, we see that the linear density would also be 12.5 c/m-sh whereas the spatial density would be 50 / (25 m x 4 m) = 0.50 c/m^2; four times larger. The spatial density incorporates the amount of sea floor surveyed and has more significance biologically.

The mean density over a given area was treated as a ratio estimator (Cochran 1977).

$$\bar{d} = \frac{\sum_t d_t * s_t}{\sum_t s_t} \tag{1}$$

where $\bar{d}$ is the estimate of the mean density, d_t is the density for transect t and s_t is the size of transect t. It should be noted that for the linear densities, all transects are the same size and Equation (1) reduces to a simple average. Bootstrapping and bias-corrected accelerated percentile intervals (Efron and Tibshirani 1993) were used to establish 90 percent confidence bounds on $\bar{d}$.

Where possible, transect-locations were re-used in an attempt to filter out spatial variability in sea cucumber abundance. However, as illustrated in Figure 8, it was found that, from year to year, length and depth-profiles of a transect could change. The reasons for the differences include different tidal cycles that change the diveable depth-range, difficulties in recording and finding the exact transect position and challenges in keeping station while laying transect lines with tidal currents and weather.

Year-to-year changes in transect locations can have an impact on survey results that are unrelated to changes in sea cucumber abundance. In an attempt to isolate changes in abundance, data from each transect was trimmed so that it had the same length and a similar depth-profile for every survey-year. The process, termed 'truncation', applied to each transect was as follows:

1. On the basis of the chart-datum depth, a common depth range between years was determined.
2. For each year's data, the longest continuous segment in this range was determined.
3. The shortest of these segments was the target-segment.

4. For the other years, least-squares was used to identify the transect-segment with the same length and the closest depth-profile.
5. Transect data were truncated to these segments.

Truncation generally resulted in transect length being reduced by about a third (Figure 9). As expected, truncation caused linear density to decrease or stay the same. The decreases can be large (see Figure 9 for example). The truncations can cause spatial density to increase or decrease. Usually it increases, implying that sea cucumbers are rarer at the tips of the transects. The change in spatial density can be significant. Generally, the change in spatial density is less than for linear density.

1.3.2.2 Pairwise Comparison of Densities

Changes in density over time were evaluated using of pairwise comparisons. The approach of estimating the mean of differences between paired-transects minimizes the impact of transect-by-transect variation and is at least as powerful as investigating the change in overall mean density.

The estimated mean change in density was calculated as

$$\bar{\delta} = \frac{\sum_t \delta_t * s_t}{\sum_t s_t} \tag{2}$$

where δ_t is the difference in density for a single transect between survey years and s_t is the size of the transect. In calculations for spatial density, some transects were longer than others, and these have a larger influence on $\bar{\delta}$.

We are interested in whether the average change was negative ($\bar{\delta}$ <0). Therefore a suitable null hypothesis is that the mean of the change in density is greater than or equal to zero ($H_0 : \bar{\delta} \geq 0$).

Two methods were used to estimate p-values: classical statistical methods, based upon the assumption of a normal distribution, and bootstrapping and bias-corrected accelerated (BCa) percentile intervals (Efron and Tibshirani 1993).

The estimated standard error for $\bar{\delta}$ was calculated as

$$sterr(\bar{\delta}) = \sqrt{\frac{N-n}{N} * \frac{1}{n*(n-1)} * \frac{\sum_t s_t^2 * (\delta_t - \bar{\delta})^2}{(\bar{s})^2}}$$

where $\bar{s}$ is the mean transect size, n is the number of surveyed transects and N is the number of transects that could fit in the study area. Since only a small fraction of the potential transects were surveyed, $\frac{N-n}{N} \approx 1$, the equation reduces to

$$sterr(\bar{\delta}) = \sqrt{\frac{1}{n*(n-1)} * \frac{\sum_{t} s_t^{2} * (\delta_t - \bar{\delta})^2}{(\bar{s})^2}} \quad (3)$$

The resulting t-value was $\frac{\bar{\delta}}{sterr(\bar{\delta})}$ and $(n-1)$ was used to approximate the number of degrees of freedom. The p-value was taken from a table of values for the Student-t distribution (Beyer 1981). In the second approach, bootstrapping and BCa limits were used to estimate the probability that the mean of δ is greater than zero. This probability was also used as a p-value.

1.4 Results

An example of the impact of truncation on linear density is shown in Table 4. As expected, linear densities are smaller when the transects are truncated. Truncated linear density estimates for Gil/Gribbell were 20% less than the estimates of linear density that use the full dataset. Differences for other survey areas range from 15% to 30%. In this particular example, the changes in density are more statistically significant when the transects are not truncated. All results presented henceforth are of truncated data. It is important to keep in mind that the data were truncated for the purpose of conducting pairwise comparisons between survey years and do not represent the best estimate of density in a given year.

Linear and spatial density estimates were compared, for the Area 7 surveys only, to illustrate the difference between these two estimates (Table 5). There was little difference between the two units of density in the number of cases of statistical significance between years; density expressed in spatial units shows slightly more significance than the linear density analysis. A similar difference between linear and spatial density estimates was seen in Gil/Gribbell survey results (not shown), while all other survey areas had no difference in significance between linear and spatial results. Since spatial density estimates depict biological changes to a better degree, further comparisons of density changes will only use spatial density estimates.

1.4.1 Trend in spatial density between years

Changes in mean density were evaluated for pairs of years at the same location (Table 5 and 6). When entire surveys are considered (pooled Subareas) the estimated mean change is always negative. Sometimes, but not always, these mean-changes are large enough to be statistically significant. Due to truncation, each p-value in Table 5 applies to a small sub-set of the available data. It is likely that if an appropriate analysis was applied to the entire pool of data, the result would show that abundance has declined significantly for all of these study-areas.

In Area 7 and Gil/Gribbell, there was approximately a 10% decrease in density in the eight-year interval from the first to the last survey. In the remaining open areas that had only two surveys over a four-year time interval, fractional declines were 12.5%, 23%, 23% and 22% for Trutch, Fitz Hugh Sound, Area 12 and Tofino, respectively.

1.4.2 Relationship between harvest history and trends in density

Quotas in the sea cucumber fishery are set by Quota Management Areas (QMA), which are made up of groupings of Subareas. Harvest occurring in a QMA is not distributed equally between Subareas, and large portions of a quota may be harvested from one or a few Subareas. Annual calculated quotas and landings for each surveyed Subarea, standardized as tonnes of round weight per kilometre of shoreline, are shown in Figure 10. Landing data prior to 1998, the year that surveys began on the coast, were pooled and averaged over the period since landings were first reported in BC.

Comparisons between the trend in density over time and the harvest history in a Subarea revealed no consistent relationship. In Gil/Gribbell, Subareas 6-6 and 6-7 were harvested above the calculated quota in three of the five years spanning 1999 to 2003 (Figure 10) and both showed significant decreases in density (Table 6a). Similarly, in Area 7 Subarea 7-17, harvests were greater than the calculated quota in three of the five years from 1998 to 2002 (Figure 10) and again, there was a significant decrease in density over that period (Table 5). However, this trend of density-decrease coinciding with harvests above the calculated quota was not always, or even usually, observed. In Area 7 Subarea 7-17, harvests were greater than the calculated quota for most years from 2002 to 2006 (Figure 10), yet density increased slightly but not significantly (Table 5). Area 7 Subarea 7-30 was harvested far below the calculated quota between 1998 and 2002 and yet there was a small, non-significant density decrease during this interval (in 2002, density was measured before the large harvest that year). Then, during the next interval (2002 to 2006) the same Subarea was harvested far above the calculated quota and yet only a small, non-signficant decrease was observed (Table 5). We see that Fitz Hugh Sound was usually harvested below the calculated quota from 2002 to 2006 (Figure 10), and there the density in four of the six Subareas decreased significantly (Table 6c). Tofino Subareas 24-5 and 24-7 were harvested over their respective calculated quotas (Figure 10); the density increased in 24-5 by 11% and decreased significantly by 53% in 24-7 (Table 6e).

1.4.3 Transect locations associated with and without fishing

There are two criteria for deciding whether a transect is recently harvested (Table 7). Both these criteria give similar results. For Gil/Gribbell and Area 7, the harvested transects have a larger mean decline in abundance than unharvested transects. For Fitz Hugh Sound, Area 12 and Tofino there is no statistically significant change in abundance between harvested and unharvested transects. For Trutch, the stock does better at the transect locations where there has been harvest. Overall, there is no clear indication that the mean decline in abundance is worse in transects locations that experienced recent harvest.

1.5 Discussion

The data from these surveys indicate a general decline in abundance has occurred over the time-span of study. The decline is in the range of 10% to 23% (Tables 5 and 6). There was no clear relationship between harvest history and trends in density between years. Based on this data, both heavily harvested and lightly harvested Subareas could either increase or decrease in density. Similarly, the analyses attempting to isolate the

effect of harvest by defining harvested and unharvested transects are also inconclusive. Sometimes harvest appears to result in abundance declines, while at other times abundance appears to increase where there has been harvest. This inconsistency in trend or pattern could be a result of uncertainties in the exact location of harvest and the harvest amount, combined with the possible effect on densities of removals nearby but outside of the defined 400 m buffer.

Precision of the 90% confidence bounds of the mean density estimates range from 9% to 13% of the mean for Gil/Gribbell, Trutch, Area 7 and Fitz Hugh Sound. Surveys in Area 12 and Tofino are less precise at 17% to 19% and 16% to 26%. With the exception of the 2005 data from Tofino (26%), these levels of precision are acceptable, considering that the lower bound is used to estimate biomass for quota-setting purposes. The sampling intensity of one transect per 2 km of shoreline is therefore an adequate sampling intensity for sea cucumber populations and should continue to be the target in abundance surveys.

It is important to note that all of the open survey areas were commercially harvested before the first surveys were conducted. The initial estimates of density were therefore not of virgin populations. Consequently, population declines observed in this study (10% to 23% of the estimates of initial surveyed populations) are probably not as high as what the declines would have been from the unfished state.

2 Changes in Population Density in Experimental Fishery Areas

2.1 Background

Four long-term experiments are being conducted along the BC coast to measure the effects of various levels of harvest on sea cucumber population density and weight distribution. Exploitation rates are used in calculating quotas for the commercial sea cucumber fishery. Currently, populations are being harvested at a conservative rate of 4.2% of estimated biomass, borrowed from analyses conducted by Washington State researchers and the most conservative estimate available. In the fishery experiments, populations were harvested at 0%, 2%, 4%, 8% and 16% of surveyed population size in sites measuring 10 km of shoreline length. The sites undergoing these five different exploitation rates are hereafter referred to as Sites 0, 2, 4, 8 and 16. Here, we present the results of density surveys in these EFAs; Section 4 presents the results of weight analysis.

2.2 Data Description

2.2.1 Survey and Harvest History

Harvesting had not occurred in the Subareas where experimental fisheries were located for at least five years prior to the start of the projects. Jervis Inlet was last harvested in 1988 with a season total of 7,498 kg (round weight) in sea cucumbers landed. The last season that Zeballos was harvested was in 1991 with a total of 30,758 kg landed. Laredo Inlet and Tolmie Channel were last harvested in 1993 with 14,511 kg and 6,196 kg

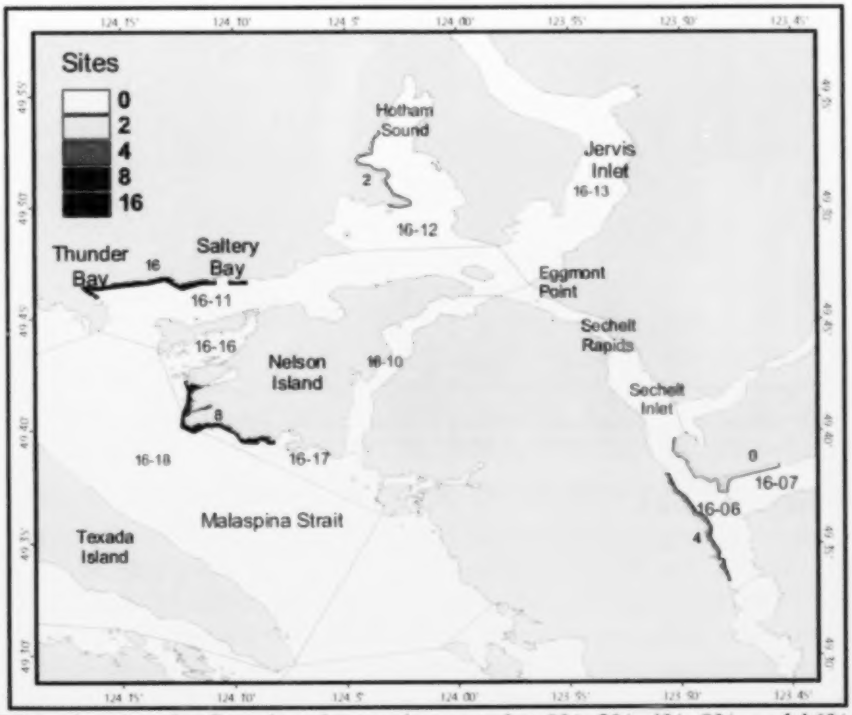
landed, respectively. We therefore considered the four populations to be in a relatively natural or virgin state.

Each EFA was divided into five sites, one for each of the harvesting treatments. The first density survey that was conducted in each of the sites provided the data required to estimate the population size in each of the 10 km lengths of shoreline. These population sizes were then used to calculate the number of animals to be removed from each site, depending on their harvest rates. Experimental quotas in the EFAs are based on proportions of population size rather than biomass, as for commercial quotas, for ease of catch monitoring during the experimental fisheries and also to avoid introducing error from mean weight estimates in biomass estimates. Quotas were kept constant across years. Biosamples were collected as part of these density surveys to estimate mean weight per site; these results are presented in Section 4.

2.2.2 Description of Survey Locations

Jervis Inlet - Area 16

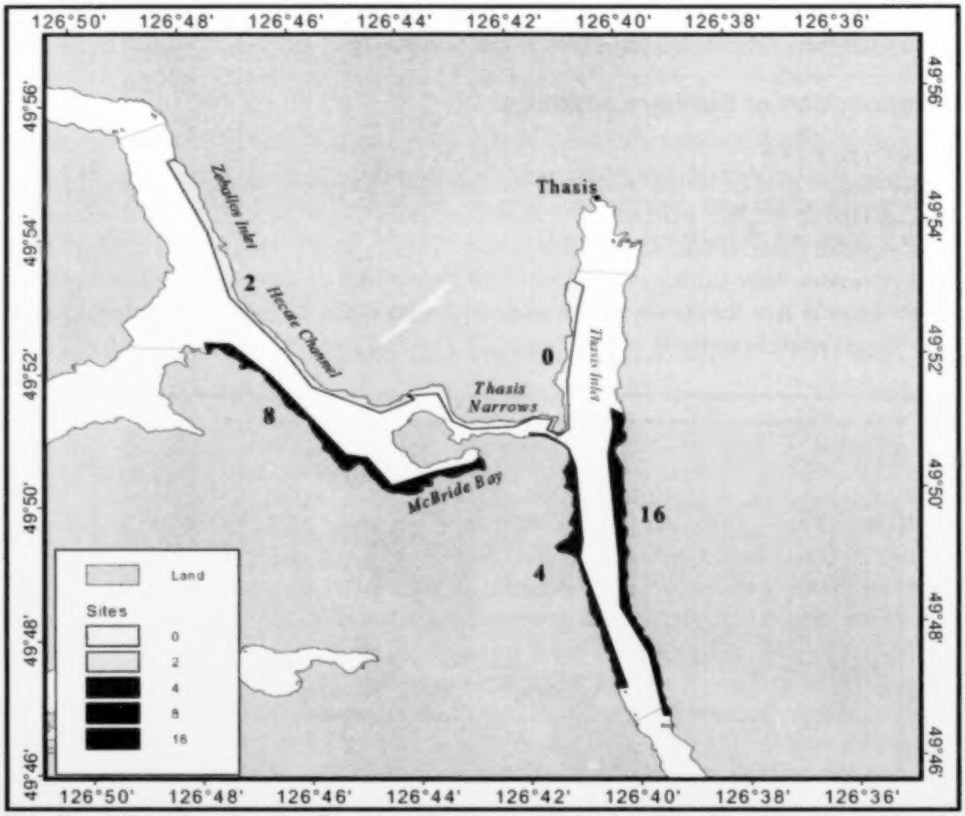
This EFA includes part of Jervis Inlet (Saltery Bay and Hotham Sound), Sechelt Inlet and west Nelson Island; the five sites were located in very different habitats (Figure below). The EFA includes parts of statistical Subareas 16-6, 16-7, 16-11, 16-12, 16-16, 16-17, and 16-18. All sites were initially surveyed in 1998 as a trial to help determine the appropriate sample size for surveys associated with experimental fishing (Campagna and Hand 1999).



Jervis EFA, showing the five sites that are harvested at 0%, 2%, 4%, 8%, and 16%.

Zeballos Inlet – Area 25

This EFA was located on the West Coast of Vancouver Island, in Zeballos and Tahsis Inlets, including portions of McBride Bay and Hecate Channel. It incorporates statistical Subareas 25-8 and 25-9. Sites 0, 4 and 16 were located in Tahsis Inlet, characterized by moderate to steep slopes with soft substrates, an abundance of silt, and low species abundance and diversity. Site 8 was characterized by a low current regime, moderate slope with soft substrates near the head of the bay and boulder and bedrock walls near Hecate Channel. McBride Bay also has low species abundance and diversity. Site 2, had a moderate slope, soft substrate with occasional bedrock and boulder walls and low species diversity.



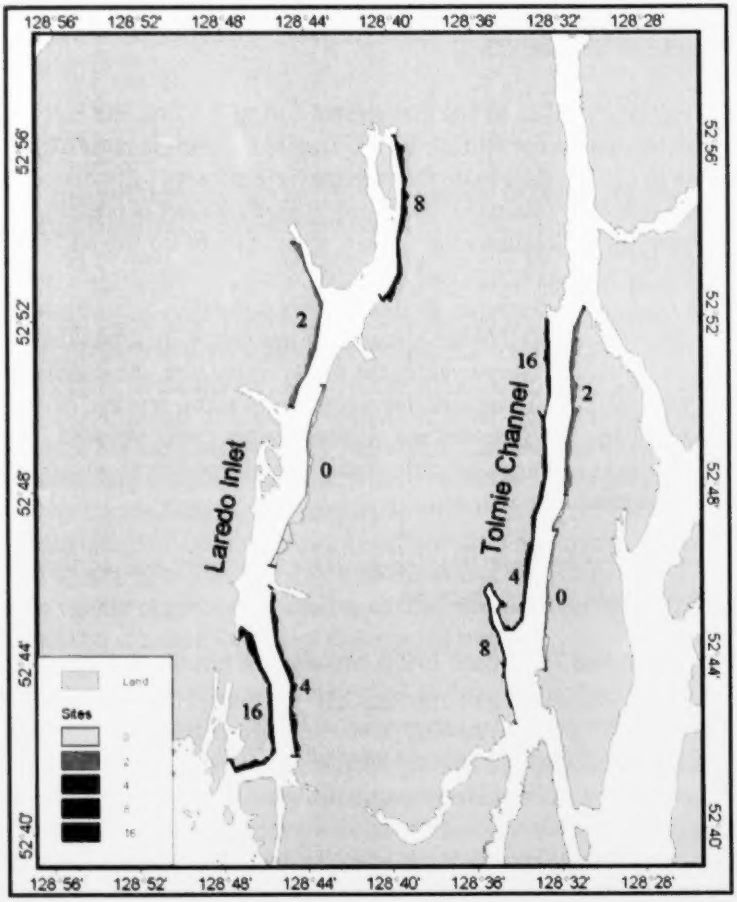
Zeballos EFA, showing the five sites that are harvested at 0%, 2%, 4%, 8%, and 16%.

Tolmie Channel – Area 6

Tolmie Channel is a large channel located in statistical Subarea 6-20 on the central coast of British Columbia. The five sites are fairly homogeneous in topography except where Sites 8 and 4 meet in Cougar Bay, which is characterized by soft substrate and gentle slope. It has shores with a gentle to steep slope, underwater topography consisting of boulders mixed with sand and shell and very dense algae cover. There are stronger current regimes and greater diversity in fauna and flora than seen in Laredo Inlet.

Laredo Inlet – Area 6

Laredo Inlet is a very sheltered fjord located in statistical Subarea 6-19 on the Central Coast of British Columbia. It is characterized by steep rock walls on both sides and very steep underwater terrain. Site 0 was characterized by steep bedrock slopes meeting a sandy substrate between 40 and 60 feet. Fauna was not very diverse especially towards the head of the inlet near Site 2 and Site 8. Site 4 had gentle to steep slopes with bedrock to boulder substrates. Site 16 is the most diverse at its north end, with a shallow sand to cobble bay, covered by rhodolites and low algae cover. The site shoreline becomes steeper and more exposed towards the south.



Tolmie and Laredo EFAs, showing the five sites that are harvested at 0%, 2%, 4%, 8%, and 16%.

2.3 Field and Analytical Methods

2.3.1 Field Methods

Transect locations were randomly selected at the beginning of the experiment for each site, in each EFA. Transects were resurveyed at each site either 3, 4, 6 or 7 times during the experiment (Table 8). High exploitation sites (Sites 8 and 16) and the control (Site 0)

were resurveyed every two years. Low exploitation sites (Sites 2 and 4) were resurveyed every 4 years, as was established in the original protocol in 1999 (Hand and Rogers 1999). Laredo Inlet and Tolmie Channel had additional surveys conducted in all sites in 1998, Laredo Inlet and Tolmie Channel's Site 0 was re-surveyed in 2000 along with Laredo Inlet's Site 8 and 16.

Transect survey methods are as described in Section 2.3.1. for open surveys.

2.3.2 Analytical Methods

Methods for density estimation and pairwise comparison of densities between survey years are described in Section 2.3.2.

The estimated spatial densities of sea cucumbers during the first and last years of the experiment were compared for all four EFAs. Due to the simple nature of this analysis, it was not possible to use the data from the intermediate surveys (all collected data are utilized fully in Section 5, where the latent productivity model is presented). The analyses are similar to those for the commercial fishery areas, except for the addition of comparing the change in density to the change that occurred when the harvest rate was zero. Consider Jervis Inlet as an example. Between 1999 and 2007, it is estimated that the spatial density decreased by 0.076 sea cucumbers per metre squared when the harvest rate was two percent (Table 9c). However, in the unharvested site, the estimated change in spatial density was +0.018. Therefore the net-effect of a two percent harvest is estimated to be a decline of 0.018+0.076=0.094 sea cucumbers per metre squared. In order to determine if the harvest had a statistically significant impact on abundance, the following null hypothesis was used:

> H0: When there was harvest, the change in mean density was no worse than the change that occurred without harvest.

Bootstrapping (Efron and Tibshirani 1993) was used to test the null hypothesis. Since multi-sampling was used, and therefore BCa methods could not be used to estimate the p-value, the p-values were derived on an empirical basis. A p-value greater than 0.05 indicates that there is not strong evidence against the null-hypothesis.

2.4 Results

Density means and 95% confidence intervals (from bootstrapping), for each EFA by site and year, are shown in Figure 11. Within EFAs, sites vary in mean density. For example, in Jervis Inlet, Site 4 had generally high density estimates while Site 8 had low density estimates in all years surveyed. Zeballos appears to be the only EFA with consistent density ranges between Sites. Between survey years, density estimates varied, both negatively and positively and some of this year-to-year variance in the abundance cannot be explained by the harvest level. None of the EFA control sites had significantly reduced density estimates between the first and last year surveyed (Table 9), but mean densities did fluctuate between years (Figure 11). Site 16 decreased in density over the years in all EFAs, two of them significantly (Jervis and Zeballos) and Site 8 also had significant

decreases in density in Tolmie Channel and Laredo Inlet (Table 9). The response to harvest in Sites 2 and 4 was mostly non-significant decreases or increases in density.

The change in density in a given site between the first and last years of the experiment were compared to changes observed in the associated Site 0 (Table 9). In Laredo Inlet, no site had declines that were greater than the declines that occurred in the no-harvest control site. In Tolmie Channel, density declines in Sites 4, 8 and 16 were significantly more than the change in density in Site 0 (which actually increased). These three sites experienced large drops in mean densities (20.1%, 53.4% and 33.8%, respectively) in this period. No site in Jervis Inlet had a density decline greater than the control site. All sites in Zeballos had significant decreases in density when compared to the large increase seen in the control site.

2.5 Discussion

While harvesting was not the only factor affecting density in our study sites, it did seem to have an impact on the density of sea cucumbers in EFAs. When an area was harvested heavily over a period of time, density declined. The 8% and 16% harvest rates appeared, at least in these EFA locations, to be reducing the population more so than natural fluctuations observed elsewhere. However, a value for the increased effect of higher harvesting rates is difficult to determine from our results. Zeballos, for example, had a large increase in density in the control site, yet the densities in other harvested sites either remained the same or declined. It is possible that the other sites may have increased if no harvesting took place but we have no way of knowing that and can only assume that harvesting eliminated any increase that would have occurred in the population had it not been harvested. The trend of decreasing density in sites with higher harvest rates may indicate that populations can sustain at least small amounts of harvest, 2% or 4% for example, without deviating too far from natural variations in density levels. There does not appear to a be visible proportional decline in tune with harvest levels, a longer time series of data would be required to extract this type of trend.

The variation seen in both harvested and non-harvested sites is likely driven by local environmental conditions, such as salinity levels, current regimes, light levels and food availability, which ultimately affect recruitment, growth and survival. Further analysis of these factors and their effects on density estimates would require a very large effort to tease out correlations between environmental conditions and density levels. The two-year gap in density estimates for Site 0, 8, and 16 and the four-year gap for Site 2 and 4 can make trends difficult to see, however more intensive monitoring may not succeed in furthering our understanding of how environmental variability affects recruitment and subsequent densities.

3 Effects of Harvest on Weight Distribution of Sea Cucumber Populations

3.1 Background

Some concern has been expressed about the effects of commercial harvesting on average sea cucumber size (D&D 2003, Humble et al. 2007). Seafood buyers, and therefore harvesters, prefer large adult sea cucumbers for ease of processing and higher market value. Sampling was conducted at each of the ten locations where density surveys were conducted, including both commercially and experimentally-harvested areas. The objectives of sampling were to determine average sea cucumber weight for biomass calculation and quota-setting, and to monitor natural fluctuations and potential effects of harvest on the size distribution.

3.2 Field and Analytical Methods

3.2.1 Field Methods

Biosamples were collected in the six open survey areas (Area 7, Fitz High Sound, Trutch, Gil/Gribbell, Area 12 Inlets and Tofino) and four EFAs (Laredo Inlet, Tolmie Channel, Jervis Inlet and Zeballos) between 1998 and 2007. The six open survey areas had three to ten biosamples collected from randomly selected transects, at four-year intervals (Table 2). In the EFAs, two transects were randomly selected in each of the five treatment sites (no harvest/control; Sites 2, 4, 8 and 16) and sampled every year whether surveyed or not (Table 8). Sea cucumbers were collected from along a transect to varying swath widths, depending in the density, to a target of 50 animals for each biosample. However, fewer animals were collected at some transects due to low sea cucumber densities or logistical sampling constraints. The sea cucumbers were longitudinally split, had their guts removed and were drained before being individually weighed, to the nearest gram, on the same day they were collected.

3.2.2 Analytical Methods

Each open area and EFA Site was analyzed separately for changes in weight, as each area appeared to have somewhat unique density and population characteristics. Split weight data were tested for normality using Kolmogorov-Smirnov's test, with a p-value less than 0.05 indicating non-normal distribution. Independent t-tests and analysis of variance (ANOVA) tests were used on normally distributed data to examine differences between sample years. If the data were not normally distributed, nonparametric Mann-Whitney U and Kruskal-Wallis tests were used. Area 7 and Fitz Hugh Sound are geographically close together and surveyed in the same years, 2002 and 2006. Mean split weights from these two areas were compared for each year.

If all sites in a given EFA contained normally distributed data, annual differences in mean split weight were compared using one-way analysis of variance (ANOVA) tests and Bonferroni post-hoc analysis. The Bonferroni analysis allowed for the identification of which years had statistically different mean split weights, and it adjusted the computed probability to account for the large number of tests being performed (Rice 1989).

3.3 Results

A total of 21,540 sea cucumbers were collected between 1998 and 2007 in the ten survey areas. Of these sea cucumbers, 16,821 (78.1%) were collected in EFAs and 4,719 (21.9%) were collected in open survey areas.

3.3.1 Open commercial harvesting areas

Area 7
Biosamples were collected from eight transects in 1998, 2002, and 2006. From these, a combined total of 1,183 sea cucumbers were weighed. Both 1998 and 2002 have positively skewed distributions, with a greater number of smaller individuals and fewer large individuals (Figure 12a). The distribution of weights in 1998 and 2002 were not normally distributed ($p<0.05$). The 18.9% decrease in mean split weight in 2002 compared to 1998 was significant (Table 10). Although mean split weight significantly increased by 5.9% between 2002 and 2006, the mean split weight of the 2006 sample was still significantly smaller than samples collected in 1998.

Fitz Hugh Sound
A combined total of 613 sea cucumbers were collected in six transect locations in 2002 and 2006. In both years, the split weight data were not normally distributed (Figure 12b; $p<0.05$). There was a significant, 9.7% increase in the mean split weight of sea cucumbers between 2002 and 2006 (Table 10).

The sea cucumbers sampled in Area 7 were significantly larger than those from Fitz Hugh Sound in both 2002 and 2006 (Table 10).

Trutch
A combined total of 300 sea cucumbers were collected from Trutch in 2001 and 2005 from three transect locations. The 2001 distribution was not normally distributed ($p=0.033$), with animal sizes fairly evenly distributed between 103 and 844 grams (Figure 12c). The mean split weight of sea cucumbers in 2005 was significantly lower than the mean split weight in 2001 (a 16.7% decrease) (Table 10).

Gil/Gribbell
A combined total of 1,401 sea cucumbers were collected from 10 transects in the Gil/Gribbell area over three years: 1999, 2003 and 2007. The size distribution had a slight positive skew in 2003 and 2007, toward smaller individuals, and neither year was normally distributed ($p<0.05$) (Figure 12d). At least one of the three years of data was significantly different from one other year of data (Kruskal-Wallis, $p<0.001$). Sea cucumber mean split weights recorded in 2003 and 2007 were significantly lower than the mean split weight recorded in 1999 (Table 10). There was no significant difference in the mean split weight of sea cucumbers between 2003 and 2007.

Area 12 Inlets
A combined total of 612 sea cucumbers were collected from six transects sampled in 2000 and 2004. Both 2000 and 2004 had normal split weight distributions (Figure 12e;

p=0.662 and p=0.228, respectively). There was no significant difference in mean split weight of sea cucumbers between the two sampling years (Table 10).

Tofino
A combined total of 302 sea cucumbers were collected from three transects in 2001 and 2005. Both the 2001 and the 2005 samples were not normally distributed (Figure 12f; $p<0.05$). The mean split weight of sea cucumbers in 2005 was significantly lower than that recorded in 2001 (Table 10).

3.3.2 Experimental Fishing Areas

Laredo Inlet
A combined total of 2,773 sea cucumbers were collected in 85 samples between 1998 and 2007. All samples in all sites were normally distributed except Site 2 in 2000 ($p<0.05$) (Figure 13a). There was a large amount of fluctuation from year to year in the mean split weight of sea cucumbers in Sites 8 and 16 (Figure 14a). Although Site 16 had large significant increases and decreases in mean split weight throughout the study (Kruskal Wallis, $p<0.000$), there was no significant difference in mean weight between the first and last years (Table 11). The drop in mean split weight of 29.5% in Site 8 between 1998 and 2007 was significant and reversed its standing from the highest mean split weight in all Laredo sites in 1998. Both Site 0 and Site 4 had gradual increases in mean split weight from 1998–2007. The 28.1% and 18.9% increases in mean split weight, respectively, were significant (Table 11). There was no significant change in Site 2 mean split weights between the first and last sampling years. In 2006 there was a sharp increase in mean split weights in Sites 2, 4, 8, and 16. This increase was mirrored by a sharp decline in weight the following year, returning mean split weights to near 2005 levels (Figure 14a). There were some density increases in smaller sized sea cucumbers over the course of sampling (Figure 15a).

Tolmie Channel
A combined total of 4,993 sea cucumbers were collected in 90 biosamples from ten transect locations between 1998 and 2007. All split weight samples were normally distributed (Figure 13b). Between 2003 and 2005, Sites 2 and 8 had steep increases in mean split weight (Figure 14b). With the exception of 2006, the sites in Tolmie Channel showed relatively stable mean split weights among years.

The mean split weight of the 1998 samples and the 2007 samples for Sites 0, 2, 4 and 8 were not significantly different. Site 16 did have a significant 23.6% decline in mean split weight between 1998 and 2007 (Table 11). This decline occurred mostly in the first two years of sampling, followed by a very gradual increase in mean split weight from 2000 to 2003. As in Laredo Inlet, there was a large increase in mean split weight in all sites in 2006, followed by an equally sharp decreases in split weight the following year. This observation can not be explained, but data recording error can not be ruled out, as a new scale was put into use in 2006. There were no obvious density increases in smaller sized sea cucumbers over the course of survey years (Figure 15b).

Jervis Inlet
A combined total of 4,664 sea cucumbers were collected in 89 biosamples between 1999 and 2007. Only Site 16 in 2006 had a normally distributed split weight distribution (Figure 13c). Mean split weights of sea cucumbers declined since the beginning of the experiments in 1999 in all study sites, except Site 8 (Figure 14c). In Site 8, the mean split weight dropped steeply between 1999 and 2002, rebounded in 2003, and remained steady until 2007 when another large drop in mean split weight was observed. The 24.5%, 11.8%, 21.2%, 20.0% and 24.4% declines in mean split weights between 1999 and 2007 were significant for Sites 0, 2, 4, 8 and 16, respectively (Table 11). The density of smaller animals increased in later surveys in Site 0, this is especially noticeable in the 2007 survey (Figure 15c).

Zeballos
A combined total of 4,391 sea cucumbers were collected in 89 biosamples between 1999 and 2007 (Figure 13d). Samples collected in Sites 2, 4, 8, and 16 had significant declines (37.3%, 21.3%, 22.4%, and 32.3%, respectively) in mean split weights between 1999 and 2007 (Figure 14d, Table 11). Declines in mean split weight were seen in all harvest sites between 2001 and 2003, a slight rebound occurred in Sites 8 and 16 in 2004 and 2005 and in Sites 2 and 4 in 2005, after which decreases continued. Site 0, where no harvesting occurred, maintained relatively consistent mean split weights throughout the study, although there was a small, non-significant 6.2% drop in the mean split weight between 1999 and 2007. The density of smaller animals increased in later surveys in Site 8 and 16, this is especially noticeable in the 2007 survey (Figure 15d).

3.4 Discussion

3.4.1 Open Areas

Mean weight of sea cucumbers decreased in most of the surveyed commercial fishing areas. In these open areas, we are restricted to snap-shots of sea cucumber weight distribution once every four years, which makes any solid trend analysis difficult. However, we can say that these sites have smaller animals now than when sampling first started. Fitz Hugh Sound was the only site to have an increase (9.7%) in split weight from first to last years surveyed. When this increase is compared to the overall 14.1% decrease in Area 7, 16.7% decrease in Trutch, 12.8% decrease in Gil/Gribbell, and 11.7% decrease in Tofino, it becomes clear that a declining trend in mean weight was predominant. The distribution of sizes in these areas reveals little on recruitment. Gil/Gribbell is the only area that had any indications of a recruitment pulse occurring. All other sites have relatively similar curves from year to year, except for many instances of a reduction in the proportion of larger sizes; this is typical of commercially fished populations..

The changes in weight-distribution cannot be correlated with fishing intensity, as there are insufficient biosample locations that were targeted by harvesters to allow for a meaningful analysis. The six surveyed areas represent a diverse range of habitats, however it does not appear that observed mean weight decreases were related to geographical location.

3.4.2 Experimental Fishing Areas

Overall, in the 20 Sites in all EFAs, 11 Sites had decreases in mean weight, seven had no significant changes and two had increases in mean weight between the first and last year of experimental harvesting. Our analysis shows no evidence of declines proportional to the harvest amounts. Tolmie Channel sites saw only small changes to split weight over the years, regardless of the intensity of harvesting. Jervis Inlet sites all showed a decline in split weight from 1999 to 2007, yet these declines were not proportional to the harvesting level and the site with the largest decline was the no-harvest site. This is also evident in Zeballos where all harvesting sites had reduced weights, yet not proportional to the amount of harvesting; the largest decline occurred in the 2% harvest site.

Sea cucumber weight in Laredo Inlet was highly variable across sites and years. These large fluctuations were particularly evident in the 8% and 16% harvesting sites. In contrast, the no-harvest site had a much clearer, increasing, trend during the course of the experiment. It is possible that these larger fluctuations are attributable to the higher harvesting rates although we do not see this pattern occurring in any of the other EFAs. Nearby Tolmie Channel saw only small changes to split weight over the years, regardless of the intensity of harvesting. The differences observed between Tolmie Channel and Laredo Inlet are interesting and strongly suggest that different coastal areas will react, or naturally fluctuate, in unique ways. This in itself could make predicting future changes in weight in unsurveyed areas difficult. Without baseline information on the structure of each coastal area it would be difficult, with our current understanding, to predict how weight distributions within an area would react to harvest.

The results of Zeballos indicate that harvesting can lead to a reduction in mean sea cucumber weight, yet this was not indicated in the other EFAs. Again this highlights the need for area specific information in order to predict how changes in weight will occur. The recovery seen in the other EFAs could be due to immigration or recruitment. The recovery from recruitment would be the slow increase in the number of smaller individuals seen in many sites and immigration is most certainly responsible for the consistent appearance of individuals in the middle weight classes.

3.4.3 Future analysis and directions

There are many possible driving factors in the decline, the increase or the stability of sea cucumber weight in these areas. Sea surface temperature, salinity levels, predation, sunlight levels, or any number of environmental factors could be causing, alone or acting in concert with harvest pressure, these changes in sea cucumber weight. Climate change or La Niña/El Niño events may result in changes to food availability or sea surface temperature that would affect sea cucumber growth. Rainfall amounts and associated salinity changes can affect different populations to different degrees, but would likely result in bathymetric migration pattern changes and possible growth impacts from leaving food-rich shallower waters. Further study and analysis of these data may produce correlations between sea cucumber size and environmental factors.

Sea cucumbers from the four EFAs differed in baseline weight. This difference in weight could be due to location or it could be the season in which the data were collected. Jervis Inlet, the area with the smallest sea cucumbers, was surveyed in January-February and

Zeballos, the area with the largest sea cucumbers, was surveyed in June. Laredo Inlet and Tolmie Channel, the middle size areas, were surveyed in September. At least part of the size discrepancy among these four sites could be a result of the digestive-reproductive cycle in sea cucumbers. In the late fall, sea cucumbers reabsorb their visceral organs and then in late winter they begin to redevelop reproductive and digestive organs and gain weight through to their peak in reproductive activity in June-August. We would expect sea cucumbers to be leanest in December and January and heaviest between June and August, and this is consistent with our data.

4 Modeling Responses to Varying Harvest Rates

4.1 Background

As outlined earlier, the paucity of life-history data for sea cucumbers precludes the use of models based on knowledge of age, growth and rates of recruitment and mortality. Sea cucumbers are, however, easy to survey and estimates of time-specific and area-specific population size can readily be made. It is possible to make use of data from the four EFAs on the coast of British Columbia (described in Section 3) to estimate the rate that sea cucumber populations are able to recover from a range of depletion-levels. The results of this analysis will produce estimates of maximum sustainable harvest rates which may be applied to the fishery.

4.2 Data Description

Data from four Experimental Fishery Areas (EFAs), described in Section 3, were used in the analysis. The sea cucumber populations in the EFAs had not been harvested for at least 5 years (Section 3.3) and hence the populations were assumed to be in a virgin state at the time of the initial surveys (see Table below).

Within each EFA there were five sites subjected to five different harvest rates. The harvest rates were of 0% (control), 2%, 4%, 8%, and 16% of the estimated virgin population, as estimated from the initial survey. It should be noted that these survey rates were targets; in some instances, due to low densities, harvesters were unable to take enough sea cucumbers to achieve the targeted harvest rates. Harvest data are available for individual sites and were condensed to the harvest (in kilograms) taken during every month of the experiment. The 0%, 8% and 16% Sites were surveyed every second year while the 2% and 4% Sites were surveyed every fourth year, over a time-span of 10 years.

Calculations were done on the basis of linear density and spatial density of biomass. Average sea cucumber weights were used to convert between biomass and population size, where necessary. For the purposes of tracking changes in density over time, transects were truncated as described in Section 2. However, where a transect was surveyed just once, year-to-year consistency was not an issue and so the entire transect was used. Entire transects from the initial survey were also used for estimates of virgin abundance, since the goal was to estimate abundance for entire sites rather than comparing estimates over time.

EFA	Transects	Estimated Mean Density at Initial Survey	
		Linear (sea cucumbers per metre of shoreline)	Spatial (sea cucumbers per metre-squared)
Jervis Inlet, 1999	108	7.469	0.183
Laredo Inlet, 1998	78	1.289	0.081
Tolmie Channel,1998	87	7.316	0.428
Zeballos Inlet,1999	75	3.763	0.166

4.2.1 Harvest and Survey History

See Section 3.2.1.

4.2.2 Description of Survey Locations

See Section 3.2.1.

4.3 Field and Analytical Methods

4.3.1 Field Methods

Data collection methods for the experimental fishing areas are described in Section 3.3.1.

4.3.2 Analytical Methods

The Productivity Model

A productivity model (Hilborn and Walters 1992, Quinn and Deriso 1999) was developed to represent the dynamics of a sea cucumber stock. The model assumes that the rate at which sea cucumber abundance can recover from harvesting is determined from the current biomass. Temporal trends in abundance were expressed as a first-order differential equation (equation 5, this section). The model was applied to each of the four EFAs. Monte Carlo Markov Chains (MCMC) were used to estimate the maximum sustainable harvest rates as well as other parameter values.

A Productivity Model requires a function for latent productivity. The latent productivity is the rate at which the biomass will increase if there is no harvest. It was assumed to have the following constraints, or characteristics:

1. The rate is zero when the biomass is zero.
2. The rate is zero when the biomass is in its virgin state.
3. There is a single maximum rate.
4. The biomass can recover to its full virgin level in a finite amount of time.

There is also the option of applying constraints to the system when stocks are almost completely depleted. It could be argued that the stock should behave in a depensatory, compensatory or even a neutral way. Of course, these assumptions can only be validated if there are data from severely depleted stocks. Somewhat arbitrarily, the fifth characteristic was set to:

5. Latent productivity is depensatory at severely depleted stock levels.

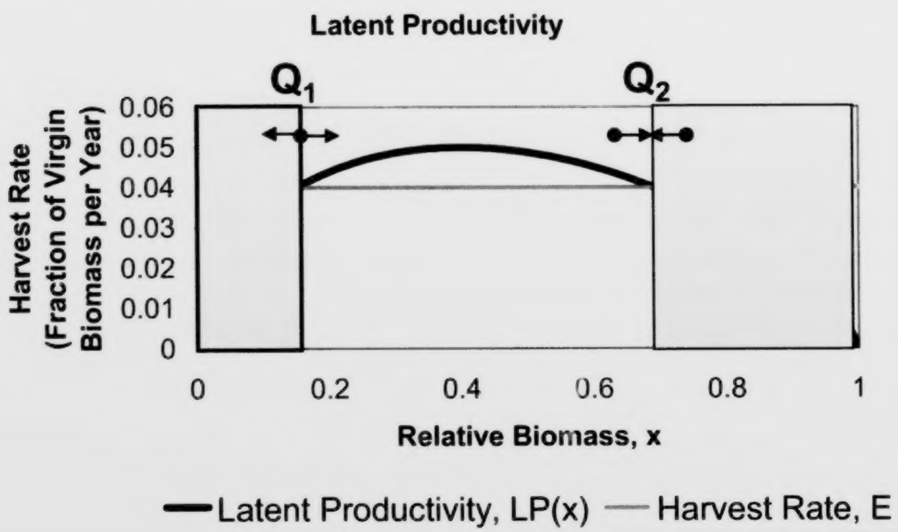
Mathematically, the fourth and fifth constraints can be expressed as:

4. $$\lim_{x \to 1^-} \left(\frac{d}{dx} \frac{LP(x)}{1-x} \right) > 0$$

5. $$\lim_{x \to 0^+} \left(\frac{d}{dx} \frac{LP(x)}{x} \right) < 0$$

Where x is the biomass expressed as a fraction of the virgin value and $LP(x)$ is the latent productivity.

This is what a hypothetical rate of latent productivity might look like in order to satisfy the five constraints. A harvest rate is also shown in the graph.



A few interesting things to note:

- When the latent productivity is less than the harvest rate (shaded), the biomass is decreasing.
- When the latent productivity is greater than the harvest rate (unshaded), the biomass is increasing.
- If the harvest rate is larger than the maximum of the latent productivity, then the fishery can not be sustained.
- If the harvest rate is less than the maximum of the latent productivity, then there are two equilibrium points where $E = LP(x)$, Q_1 and Q_2.

- The upper equilibrium point, Q_2, is stable and therefore maintainable. Small perturbations in the environment and small uncertainties in our knowledge will have a small impact on the point of equilibrium.
- The lower equilibrium point, Q_1, is unstable. Even small perturbations in the environment and small uncertainties will cause the stock to either crash or drift to the upper equilibrium.

Under the productivity model, the maximum sustainable harvest rate (MSHR) corresponds to the maximum of the latent productivity.

There were many – possibly infinitely many - mathematical functions that could have satisfied our requirements. The following mathematical function was chosen as a suitable representation of latent productivity:

$$LP(x) = F_{max} * \left(\frac{x}{x_{max}}\right)^a * \left(\frac{1-x}{1-x_{max}}\right)^b \qquad (4)$$

where

- x is the biomass expressed as a fraction of the virgin biomass; $0 \le x \le 1$, $x = 1$ corresponds to a virgin state,
- x_{max} is the biomass level where there is maximum latent productivity; $0 \le x_{max} \le 1$,
- F_{max} is the maximum latent productivity,
- $b > 0$ is a constant which controls the width of the latent productivity function. When b is small, the function has a wider peak.
- a is determined from x_{max} and b. $a = b * \frac{x_{max}}{1-x_{max}}$.

The fourth assumed characteristic is satisfied when b<1. The fifth assumed is satisfied when a < 1.

If the Harvest rate is expressed as E, a fraction of the virgin biomass, then the model becomes a first-order differential equation.

$$\frac{dx(t)}{dt} = -E(t) + LP(x) \qquad (5a)$$

Biomass is increasing if $LP(x) > E$, decreasing if $LP(x) < E$ and constant if $LP(x) = E$.

The second derivative can be expressed as:

$$\frac{d^2x(t)}{dt^2} = LP(x) * \left(LP(x) - E(t)\right) * \left(\frac{a}{x} - \frac{b}{1-x}\right) \qquad (5b)$$

Numerically, the production model can be implemented as a truncated Taylors series (Beyer 1981):

$$x(0) = 1$$
$$x(t+\Delta t) = x(t) + \Delta t * \frac{dx(t)}{dt} + 0.5 * \Delta t^2 * \frac{d^2x(t)}{dt^2} \tag{6}$$

where the time increment, Δt, is sufficiently small to get the desired level of accuracy. One month ($\frac{1}{12}\,year$) worked well.

As written, $LP(x)$ applies to the full range of $0 \le x \le 1$. However, the dataset does not necessarily span the entire range of x. For example, at Jervis, we estimate that the observed range of x is $0.30 \le x \le 1$. There is no experimental data to indicate the behaviour of the system when biomass is less than 30% of the virgin value. If $LP(x)$ is applied to small values of x, there would be extrapolation beyond the range of experimental data and the model could not be relied on to make accurate predictions. To ensure that the model remains precautionary, a truncated version of $LP(x)$ is used:

$$F_{truncate}(x, x_{truncate}) = \left\{ \begin{array}{c} LP(x) \mid x \ge x_{truncate} \\ 0 \mid x < x_{truncate} \end{array} \right\}$$
$$0 \le x_{truncate} \le 1$$

where $x_{truncate}$ is a limit, based upon the available survey data. For each location, values of $x_{truncate}$ are based upon the site with the largest targeted harvest rate (i.e. 16%). For every iteration in the MCMC, x is projected over the time-range of the experiment using $LP(x)$ and the relative harvest rate (fraction of virgin biomass). The lowest value of x to occur in the time-span of the experiment is $x_{truncate}$.

With $x_{truncate}$ established, $F_{truncate}$ is fully defined for every iteration (complete set of parameter values for the models) in the MCMC. Numerical methods were used to estimate the maximum value of $F_{truncate}$ for every iteration in the MCMC. As discussed previously, these maxima represented the maximum sustainable harvest rate and therefore the MCMC resulted in a posterior distribution for the MSHR.

Under the applied truncations, an important approximation is $MSHR = \max(F_{truncate}(x, x_{truncate}))$. This is a key value in managing a fishery, since we want to be sufficiently confident that the harvest rate is less than MSHR.

The survey model

The biomass model was applied to survey and harvest data collected over a period of approximately eight years. It was necessary to create a survey model to account for random variability in the data.

For an unharvested transect, the biomass density of sea cucumbers was modelled as

$$U_{s,y,t} = G * \exp(S_s + Y_y + T_{s,t}) \qquad (7)$$

where

- G was the geometric mean of biomass density
- $S_s \sim N(0,\sigma_s^2)$ was the site effect.
- $Y_y \sim N(0,\sigma_y^2)$ was the effect of the year of the survey
- $T_{s,t} \sim N(0,\sigma_t^2)$ was the effect of the transect within the site

For a harvested transect, the biomass density of sea cucumbers was modeled as

$$H_{s,y,t} = U_{s,y,t} * x(y) \qquad (8)$$

The expected biomass of sea cucumbers in a harvested transect is the biomass density multiplied by the size of the transect.

$$B_{s,y,t} = H_{s,y,t} * s_{s,y,t}$$

- $s_{s,y,t}$ is the size of the transect

The transects were truncated to a common length and similar depth-profile, as described in Section 2.3.2.1. For linear density, all of the transects were the same size ($s_{s,y,t} = 4$). For spatial density, size depended on the transect length $L_{s,y,t}$ (after truncation) so, since each transect is 4 m wide, $s_{s,y,t} = 4 * L_{s,y,t}$.

Average weight, $W_{s,y}$, is used to convert the expected transect-biomass to the expected transect-population.

$$N_{s,y,t} = \frac{B_{s,y,t}}{W_{s,y}}$$

Average weights, $W_{s,y}$ were estimated parameters in the model, however prior distributions based upon biosamples were used.

$N_{s,y,t}$ represents a medium-term average population. In reality sea cucumbers are mobile and the number of sea cucumbers in a transect changes from day to day. On the day of a survey, the observed number of sea cucumbers was assumed to have a poisson distribution:

$$O_{s,y,t} \sim poisson(N_{s,y,t})$$

Many of the quantities in the model are expressed as fractions of the virgin biomass. There are two indicators of virgin biomass. Firstly, virgin biomass must be consistent with the observed changes in biomass density, the recorded harvest, the production model

and the survey model. Secondly, the posterior distribution must be consistent with results of the original surveys when the sites are assumed to be in near-virgin states.

Virgin biomass density is treated very similarly to non-virgin density. The differences are:

- For virgin density, only data from the initial surveys are used.
- For virgin density, data from entire transect is used. This affects the number of sea cucumbers in the transects, the spatial-size of the transects and the area of the sites.

For a given transect location, the expected virgin biomass density is modelled as:

$$^{v}U_{s,t} = {}^{v}G * {}^{v}s_{s,1,t} * \exp(S_s + Y_1 + T_{s,t})$$

- ${}^{v}G$ is a geometric mean of the biomass density for untrimmed transects
- $S_s, Y_1, T_{s,t}$ and $W_{s,1}$ are the same values as used elsewhere in the model
- In this case, the size of a transect is taken the first time it is surveyed. For linear calculation, the size of each transect is 4 metres wide.

The expected virgin transect-population is modelled as: ${}^{v}N_{s,t} = {}^{v}U_{s,t} / W_{s,1}$. As with the trimmed transects, the observed number of sea cucumbers is assumed to have a poisson distribution: ${}^{v}O_{s,y,t} \sim poisson({}^{v}N_{s,y,t})$

For any site, the estimated virgin biomass is:

$$V_s = {}^{v}G * \Omega_s * \exp(S_s + Y_1 + \tfrac{1}{2} * \sigma_t^2)$$

- Ω_s is the size of the site.

For linear calculations, Ω_s is the associated coastline length, C_s. Coastline lengths were the same whether virgin or non-virgin biomasses were calculated. Coastline lengths were measured using digitized shapefiles created from Canadian Hydrographic Service charts of the Canadian Pacific region. The length of coastline to be measured was determined from the original boundary limits established for each site in the first year they were surveyed. Using ArcGIS 9.2, each site in each EFA had the total length of shoreline traced from boundary point to boundary point. Any large islands located along the shoreline were included in the shoreline measurement, Ω_s.

For spatial calculations, Ω_s is an area; the coastline length times the mean transect length. As mentioned above, coastline lengths were estimated with a high degree of precision and the corresponding uncertainty was ignored.

In the spatial calculations, mean transect lengths affect site-size and hence virgin biomass and the harvest rate. As such, mean transect-lengths could be treated as just another set

of parameters that need to be estimated to make the model work. However, assertive prior distributions were required to keep the mean transect-lengths in a range that was consistent with transect-lengths measured during the surveys. The prior distributions for mean transect-length were generated as follows:

> Data from the initial surveys were used. For each site, bootstrapping and bias-corrected accelerated (BCa) (Efron 1993) confidence limits were used to generate an estimate, μ_L, and standard error, σ_L, for the mean transect length. In the prior distribution, the mean transect length is restricted to the range $(\mu_L - 2*\sigma_L, \mu_L + 2*\sigma_L)$.
>
> The prior distribution was established using $z \sim beta(\frac{3}{2}, \frac{3}{2})$ as a random variate. z has a mean of ½, a standard error of ¼ and a range of $(0,1)$. The quantity used to represent mean transect length was $M = \mu_L + (z - \frac{1}{2}) * 4 * \sigma_L$.

Estimates of mean transect length are shown in Figure 16.

For spatial calculations, the size of an area is $\Omega_s = C_s * M_s$

It should be noted that the same site effects, S_s, are used for the virgin-calculations as for the rest of the model. As a result, there is an implicit assumption:

- When transects are trimmed, abundance in the remaining transect-segments are similar to the trends in the parts of the transect that got trimmed off.

Applying the model

The model was applied to individual EFAs. Linear and spatial versions of the model were applied to each EFA. Appendix 3 shows a Directed Acylic Graph (DAG) for the combined model.

The first stage of the analyses was to generate information about the parameter-values that are needed to explain the observed data. The model and the data were incorporated into a Monte Carlo Markov Chain (MCMC) in order to estimate a posterior distribution for the parameters of the model. The MCMC was implemented through WinBUGS (Spiegelhalter et al. 2003).

The next stage was to generate values for $x_{truncate}$. The latent productivity model was run with $F(x)$ on the data from Site 16 for the duration of the experiment. For each iteration of the MCMC, the minimum value of x was recorded. These minima were used as $x_{truncate}$.

The final step was to use $x_{truncate}$ and the probabilistic variables to generate posterior distributions for MSHR and the abundance of sea cucumbers under various management strategies. The fit of the model was evaluated according to the Deviance Information

Criterion (DIC) (Gelman et al. 2003). A smaller DIC indicates a better fit of the model to the data.

4.4 Results

The posterior distribution for the truncated latent productivity curves for all four EFAs are shown in Figure 17. For Laredo, the shape of $LP(x)$ is poorly defined and the equilibria between harvest and latent productivity are difficult to distinguish. For the other three EFAs, maximum latent productivity occurs at some point outside of the data-range. $x_{truncate}$ and $F_{truncate}$ are important in the model because they limit latent productivity to that demonstrated in the data.

The most important product of the model is the maximum sustainable harvest rate (MSHR), expressed as a fraction of the Year-0 biomass (Table 12). For each EFA, we are able to establish a maximum sustainable harvest rate. As an example, for Jervis-spatial, we are 99% confident that the maximum sustainable harvest rate is greater than 0.067 of the virgin biomass, using the spatial density calculations. With the exception of Laredo, MSHR is similar between EFAs and the one-percentile of the MSHR (spatial estimate) ranges from 0.067 to 0.103 of virgin biomass per year. Laredo is considerably lower, with a one-percentile MSHR of 0.035.

For Laredo and Zeballos, there is good agreement between the linear and spatial results. This corresponds to mean transect lengths that are about the same for each site (Figure 16). For Jervis, Site 8 has a very long mean-transect length compared to the other sites. For Tolmie, Site 4 and Site 8 have longer mean transect lengths. These differences in mean-transect length propagate into differences of site-size, virgin biomass and exploitation-rates (Figure 18). Differences in exploitation rates affect the apparent rates of latent productivity. Therefore estimated latent productivity is expected to differ between spatial and linear calculations if transect lengths are inconsistent between sites.

Figure 19 shows median values of the posterior distributions for the biomass projections. Annual harvest rates of 3.5%, 4.2%, 6.7% and 14% of virgin biomass per year were considered. The chosen harvest rates are important values drawn from the model results, as follows: the 3.5% harvest rate is the lowest MSHR from the analysis of all four EFAs, the 4.2% harvest rate is current rate used in quota calculation, the 6.7% harvest rate is the lowest, non-Laredo, MSHR and the 14% harvest rate was chosen as it is higher than any of the sustainable harvest rates. Harvest is spread out over the entire year. Stocks start out in a virgin state, are subjected to a harvest for 75 years and then there is no harvest for 25 years. In the figure, we see how limits in the available data ($x_{truncate}$) have been incorporated into the predicted effects of harvest. Laredo has the lowest sustainable exploitation rate (Table 12, Figure 19) and may not even be able to withstand the current target of 4.2% of virgin biomass per year. Tolmie and Zeballos can withstand a 6.7% annual harvest rate for 75 years with 99.5% confidence. Jervis can withstand a 6.7% annual harvest rate for 75 years with 90% confidence (Figure 19). Based on these results, the current exploitation rate of 4.2% applied to the commercial fishery appears to be conservative.

At a 4.2% harvest rate, the model predicts abundance will stabilize at 75 to 85 percent of virgin biomass, with the exception of Laredo. At a 6.7% harvest rate, biomass is expected to stabilize at about 60 percent of virgin biomass, with the exception of Laredo. A 6.7% harvest would be sustainable for Tolmie and Zeballos, and possibly for Jervis, but for Laredo, there is not a high level of confidence that even 4.2% is sustainable. At a 14% harvest rate, abundance is likely to go below the range of our experimental data, at which point we conservatively assume that latent productivity goes to zero and the stock crashes.

Figure 20 compares MSRH to estimated virgin biomass-densities for the four EFAs. From the shape and dimensions of the data clouds, it is apparent that densities are estimated to a higher degree of accuracy than is MSHR and that, within an EFA, there is very little correlation between density and MSHR. The separation of the data clouds along the X and Y axes illustrates that low MSHRs are associated with low biomass-densities. Laredo EFA appears at the lowest end of the range and is somewhat of an outlier. As already indicated Laredo appears to be unproductive habitat for sea cucumbers and likely would not be chosen as a harvest area by fishermen. The next most conservative MSHR is from the Jervis EFA, with biomass densities probably higher than 1.5 kg per metre or 0.02 kg per metre-squared.

Table 13 shows MSHR expressed as kilograms of sea cucumber per year (linear and spatial). Again for Jervis-spatial, we are 99% certain that the maximum sustainable harvest rate is greater than 8105 kilograms per year. As expected, Laredo has by far the lowest sustainable harvest rates; densities are low and the MSHRs are low. For Tolmie, agreement between linear and spatial results is poor – probably related to issues of mean transect-length.

It is also useful to look at the posterior distributions of $x_{truncate}$, since these values give an idea of the data range that has been observed in the experiments (Table 14). If biomass falls below $x_{truncate}$, then there is no direct evidence that latent productivity will occur. In the spatial results for example, we are 99% confident (given the assumptions of the model) that latent productivity will occur as long as the Jervis-biomass is kept above 34% of the virgin value. Therefore it is desirable to have confidence that biomass is greater than $x_{truncate}$.

Figure 11 compares 95% confidence intervals of mean densities estimated from the model to those generated directly from the survey data (Section 3). The two sets of confidence intervals are different because the model acknowledges year-to-year variability (Table 15, for example) and provided corrections for that variability, whereas the mean densities from Section 3 were not adjusted for year-to-year variability. Year-to-year variability can occur for very pragmatic reasons, such as diving conditions during the surveys. A less obvious reason for the difference is that the model assumes a lognormal distribution for within-site variability. With a lognormal distribution, a large degree of variability results in a larger mean. For Jervis, the estimated value of transect variability (σ_t) is large (Table 15) and the model results in larger estimates of biomass

density than the bootstrapping calculations. For Tolmie, the estimates of σ_t are comparatively small and the estimated densities for the model calculations can be smaller than for the bootstrapping calculations.

Over the course of the fishery experiments, the analyses were repeated as more data became available. As more data are included in the analyses, the estimated posterior distributions are expected to get narrower and the corresponding low quantiles should stablize or increase. Table 15 demonstrates how results evolved as datasets grew. Each of the four EFAs were analyzed with data up to 2005 and again with data up to 2007. When the 2005 results are compared to the 2007 results, the one-percent quantiles of MSHR were either stable or increased – as theory predicts. Laredo and Tolmie Channel were also analyzed with datasets to 2003 only. When both the 2007 and 2005 data were omitted, some of the low-quantiles became larger – indicating that in 2003 there was insufficient data to give reliable results.

4.5 Discussion

Assumptions of the model include:

1. **Virgin biomass is a stable quantity that can be estimated over the duration of the experiment.** Estimates of σ_y^2 are given in Table 15 and indicate that over the duration of the experiment, there is measurable interannual variation in the estimated biomass. Figure 11 also demonstrates how biomass estimates changed even where there was no harvest (Site 0's). There may also be longer term trends in virgin biomass due to factors such as climate change and the emergence of sea otters in the EFAs. Therefore, the estimates of virgin biomass from the initial surveys may not represent the maximum possible, as assumed in the model.

2. **Latent Productivity is determined entirely from factors internal to each site in the EFAs.** Latent productivity is a balance of natural mortality, net migration into a site, growth of individual animals and rates of reproduction. Natural mortality is unlikely to be affected by factors outside of a site. Net migration likely occurs but is expected to be low since sea cucumbers have limited mobility. The effect of immigration into a site would be an overestimate of the latent productivity function, but this may be balanced somewhat by movement of animals to outside of the site. Rates of reproduction are likely affected by external factors. There is every reason to expect that interannual variations in environmental conditions would be reflected in recruitment success of these broadcast spawners with long larval periods (Cameron and Fankboner 1989).

3. **Latent productivity responds immediately to changes in biomass**. If the growth of sea cucumbers is food or space limited, there could be immediate changes to latent productivity whenever biomass changes. However, the lagtime required for a population's reproductive efforts to be visible as recruitment into the harvestable biomass, approximately 5 to 6 years (Fankboner and Cameron 1988), was not taken into account in the modelling. The model looks for instant recruitment, but in reality we would not expect to see the effect of the first year of harvest until year five of the experiments. Earlier models incorporating a lag in

response were tested; however the results were unsatisfactory, perhaps because of the loss of about half of the time-series of available data, which is already limited. However, the impact of this instant-recruitment assumption is that estimated MSHR is conservative. If we are assuming that what we observe in the EFAs is a recruitment response, when in fact we don't expect to see any change in recruitment response for the first few years, the modelled latent productivity will tend to be pulled down. Where latent productivity depends on reproduction, the effect of a change in biomass will be delayed.

Two important values can be taken from Figure 17. The first important value is the MSHR at the height of the curves. Using Tolmie as an example, the analysis has indicated that there is a 99% probability that MSHR<12%. Managers may chose to limit the harvest rate to less than 12% of virgin population per year. The second important value is the location on the x-axis of the peak of latent productivity. This is a natural choice for a limit reference point. In the current analyses, the location of the peak is largely determined by the range of the available data. If the population-level is less than this reference point, then the population level may be unstable (see Section 5.3.2) or there may simply be no experimental data to provide guidance. Using Tolmie as an example, managers may decide to keep the population level greater than 43% of the virgin level.

One of the distinguishing features of the production model (Equation 4) is that it assumes an unharvested stock will achieve virgin biomass in a finite amount of time. Most production models (Quinn and Deriso, 1999, give examples) are based upon the assumption that an unharvested stock will asymptotically approach a carrying capacity of biomass. Equation 4 could be converted to a carrying-capacity model simply by requiring that $b \geq 1$. In fact, Equation 4 can be made equivalent to the familiar Grahm-Schaefer model by setting $b = 1$ and $x_{\max} = \frac{1}{2}$. Overall, Equation 4 is a flexible model with very convenient parameterization.

The four EFAs span a range of habitat types, including central coast fjord (Laredo) to central coast large/steep channel (Tolmie) to south coast combination channel and open shoreline (Jervis) to west coast of Vancouver Island channel (Zeballos). The physical environments (e.g. water flow, salinity, food availability) that would have influence on sea cucumber productivity (e.g. recruitment success, growth rate) are likely quite different in each of these habitat types, and the difference in density and mean sea cucumber weight between EFAs is probably a reflection of this variation.

It appears that all of the EFAs, except the very low-density Laredo Inlet, can sustain an annual harvest rate of 6.7% of the virgin biomass per year (Figure 20 and Table 12). It is unlikely that low-density areas such as Laredo Inlet would be commercially-viable, even at 6.7%, however it is suggested that sea cucumber harvest not be contemplated where the biomass densities are very low. Minimum biomass-densities of 0.020 kg/m^2 (spatial) and 1.5 kg/m (linear) were shown to be associated with areas that could support harvest rates of 6.7%.

5 Geographical Analysis of Commercial Fishery Harvest Patterns

5.1 Background

Increased knowledge of how the sea cucumber dive fishery targets different available segments of coastline is necessary for managers to assess impacts on populations and metapopulations. The commercial sea cucumber fishery has been confined to 25% of the total BC coastline since 1998 and, since then, has taken place on an annual basis. On this 25% of the coast, harvesters are free to select the areas they wish to harvest to fill quotas set on a Quota Management Area basis. The collection of geo-referenced harvest effort data has provided an uninterrupted time-series of fishery spatial data. The fleet dynamics and fishing effort data were analyzed to accomplish the following:

1. Update and refine the estimates of shoreline harvested that were originally reported in Humble et al. 2007
2. Examine the spatial movements of the fishing fleet: do they fish the same sections of shoreline every year or do they move around from year to year?
3. Explore fishing patterns relative to the distribution of sea cucumber populations from survey data. Are most or all high-density areas subject to depletion or are there pockets of high cucumber density that do not get harvested and thus act as natural spawning reserves.

5.2 Data Description

Data used in this analysis are the geo-referenced harvest logbook information, submitted by fishermen as a condition of licence. Standardized harvest charts are completed by indicating the start and end locations for individual dives; these marked locations are digitized annually by the service bureau D & D Pacific Fisheries and spatially linked to the individual fishing events recorded on harvest logs.

Individual sections of shoreline may be fished by more than one vessel or fished multiple times by the same vessel within a given year. To prevent adding the shoreline length of the same section of shore more than once in the annual estimates of total shoreline fished, the spatial data were 'dissolved' to eliminate the overlapping sections. Therefore, the measurement of dissolved shoreline is the amount of shoreline harvested at least once in a given year, but possibly more times.

A second metric of harvesting patterns and effort was developed using individual harvest logs, summed by year for the years between 1998 and 2006. This "undissolved shoreline" sums all fishing events, and therefore does count lengths of shoreline more than once if they are harvested more than once.

5.3 Analytical Methods

5.3.1 Proportion of shoreline harvested

The measured lengths, in metres, of dissolved shoreline harvested (L_H) were summed by statistical Subarea and year. The total amount of shoreline available to harvesters (L_{TA}) is known for each statistical Subarea. The proportion of the total shoreline in a given Subarea that was harvested at least once in a given year (proportion of dissolved shoreline harvested - *PDSH*) was calculated as:

$$PDSH = \sum L_H / L_{TA} \qquad (1)$$

The proportion of dissolved shoreline harvested was analysed in four ways. The first two methods calculated the *PDSH* for each statistical Subarea:

1. The mean of Subarea *PDSH* values for Subareas that were targeted by harvesters was calculated for each year between 1998 and 2006. This indicated the average amount of shoreline harvested when a Subarea was targeted.
2. The mean of Subarea *PDSH* values for all Subareas open to fishing was calculated for each year between 1998 and 2006. This demonstrated the average amount harvesters were targeting in open areas along the BC coast.

The third and fourth methods calculated overall *PDSH* values for all Subareas combined. These calculations removed the effects of averaging proportions over Subareas that are different in size and gave the overall proportions of coastal shoreline harvested:

3. The overall annual *PDSH* values were calculated by summing the measured length of dissolved shoreline harvested and dividing by the sum of available shoreline length, for Subareas targeted by harvesters.
4. The overall annual *PDSH* values were calculated by summing lengths of dissolved shoreline harvested and dividing by the sum of available shoreline length, for all Subareas open to fishing.

5.3.2 Fleet harvesting patterns

Analysis of the sea cucumber fleet harvesting patterns among years was performed by viewing the annual dissolved shoreline harvested, in ArcGIS 9.1. This consisted of nine layer-files showing lengths of shoreline fished in a single year for each year between 1998 and 2006. A particular length of shoreline may have been harvested more than once, but was only counted once in the dissolved shoreline. Annual shapefiles were overlaid and the segments of shoreline that were fished once, twice, three-times, and four-times or more between 1998 and 2006 were summarized by Subarea.

A similar series of layer-files shows the shoreline harvested for each fishing event for the nine-year period between 1998 and 2006. Annual shapefiles were overlaid, and the segments of shoreline fished in each year were summarized by Subarea. This "undissolved" shoreline sums each harvesting event, and will count shoreline length more than once if harvested more than once.

5.3.3 Harvesting high density areas

Survey densities from the most recent survey year for each of the six open surveys were considered. Transect densities in the top 10 percentile (spatial densities >0.47 sea cucumbers/m^2; range 0.471 to 1.218 sea cucumbers/m^2) of pooled years 2004–2007 were considered 'high'. Individual quadrat densities of $\geq$1 sea cucumber/m^2 (range 1 to 4.5 sea cucumbers/m^2), the top 2.5 percentile of pooled years 2004–2007, were considered very high. These high density transects and very high density quadrats were analyzed to see whether they overlapped with areas of harvesting effort and, if so, how many years they were targeted by harvesters from 1998–2006.

5.4 Results

5.4.1 Proportion of dissolved shoreline harvested

From 1998 to 2006, a total of 96 different Subareas were available for harvest along the BC coast. Six Subareas, marked as closed, were commercially harvested; one of which was an active EFA Subarea, where no commercial harvesting is permitted.

PDSH for Subareas targeted by harvesters

The mean length of dissolved shoreline harvested over Subareas that were targeted by harvesters fluctuated, but maintained an increasing trend from 1998 to 2006. The annual mean *PDSH* in targeted Subareas ranged from 0.043 (SD = 0.0552) in 2000 to 0.136 (SD = 0.1234) in 2005 (Figure 21, black line). The overall proportion of dissolved shoreline harvested (*PDSH*) in targeted Subareas ranged from 0.035 in 2000 to 0.104 in 2005 (Figure 21, blue dashed), with an overall increasing trend. Both series showed a jump in PDSH from 2000 to 2001 and 2003 to 2004. The overall PDSH in targeted Subareas was lower than the mean of PDSHs in targeted Subareas. This would indicate that larger Subareas are harvested less intensively than smaller Subareas, which may simply be an artefact of travel logistics.

Of the 96 Subareas available for harvest from 1998–2006, 21 were targeted every year. The annual *PDSH* in harvested Subareas fluctuated widely, between 0.0004 and 0.5405 (Figure 22). Five Subareas in particular (5–4, 6–26, 7–12, 24–4, 24–7) had frequent occurrences of PDSH levels greater than 0.20.

PDSH for all Subareas available to harvesters

Not all statistical Subareas were targeted by harvesters every year; the annual number of non-targeted Subareas has fluctuated over the past nine seasons from 53 to 39. The annual mean of PDSH in all Subareas ranged from 0.026 (SE = 0.0047) in 2000 to 0.080 (SE = 0.0115) in 2005 (Figure 21, black dashed) and shows an increasing trend over the time-series. The overall *PDSH* for all Subareas ranged from 0.023 (2.3%) in 2000 to 0.077 (7.7%) in 2005 (Figure 21, green line). The results for overall *PDSH* and the mean *PDSH* for all Subareas were highly similar (Figure 21); indicating that the non-targeted Subareas must be smaller in size than regularly targeted Subareas.

Trends in PDSH

There appeared to be a three-year trend in the PDSH data (Figure 21). In all four methods of calculating PDSH, every three years there was a decline in PDSH. This decline appeared in 2000, 2003 and 2006. Following this decline (2001 and 2004), there was a sharp increase in PDSH. This trend is not an artefact of changes in quotas, as the quota levels have steadily increased throughout the time period (Figure 23). The *PDSH* were consistently below 10% until 2004 when levels above 10% were observed (mean PDSH in targeted Subareas).

The effect of increasing quota on PDSH

The ratio of total amount of dissolved and undissolved shoreline harvested to annual sea cucumber quota was calculated for each year between 1998 and 2006 to examine the effects of increased quota on shoreline targeted by harvesters. Quota has increased steadily over the time period, as results of surveys indicate higher biomass, but the ratio of shoreline fished to quota has remained relatively stable (Figure 23). The time series with undissovled shoreline harvested fluctuated more than the dissolved shoreline harvested (Figure 23). That is, there is no indication that it becomes necessary for fishermen to search more area to achieve quotas other then that accounted for by higher catch limits. Every stretch of harvested shoreline appears to be harvested, on average, approximately twice each year.

5.4.2 Fleet harvest patterns

Observations of coast-wide harvesting patterns among years indicated that harvesters tended to change their harvesting locations from year to year. One example of this as can be seen in QMA 5B from 1998 to 2006 (Figure 24). The fleet did not return to the same fishing locations year after year, and even after nine years rarely returned to the same pieces of shoreline (Figure 24 and 25). In QMA 5B from 1998 to 2006, 114.6 km of shoreline had one year of harvest effort, 42.7 km had two years, 11.5 km had three years, and 3.6 km had four years of harvest effort (Figure 25). No amount of shoreline was targeted in more than 4 years, from 1998 to 2006 (Figure 25). Coast-wide, the pattern was similar; the vast majority of the coastline had only one or two years of harvesting effort. On the BC coast from 1998 to 2006, 1,484 km of shoreline had one year of harvest effort, 559 km had two years, 224 km had three years, 93 km had four years, 37 km had five years, 7 km had six years, and 2 km had seven years of harvest effort. Coast-wide, the number of years that any piece of shoreline was fished from 1998 to 2006 did not exceed seven years.

5.4.3 Harvesting high density areas

Not all high density areas were harvested from 1998 to 2006. Out of 103 open survey transects with densities greater than 0.47 sea cucumbers/m^2, 58 were located on harvested shoreline, and 45 were located on shoreline that had not been harvested anytime from 1998 to 2006 (Figure 26). Of the 58 transects located on shoreline targeted by harvesters, 17 were harvested once and 7 were harvested twice from 1998 to 2006.

There were also high density individual quadrats within transects that did not have high overall densities. In commercial harvesting areas, 348 quadrats had very high densities. Of these high-density quadrats 187 (53.7%) were unharvested from 1998 to 2006 (Figure

27), 75 (21.6%) quadrats were located on shoreline harvested in one year only and 42 (12.1%) were located on shoreline harvested in two years from 1998 to 2006.

5.5 Discussion

The proportion of shoreline harvested for sea cucumbers has gradually been increasing during the past 10 years in concert with increases in quota levels along the British Columbia coast. Most statistical Subareas are not fished every year. Of the 96 Subareas available for harvest only 22% were harvested every year. While statistical Subareas, on a case by case basis, may not have a large proportion of their shoreline harvested, the extent of the coast that was harvested, in general, is increasing.

There were large amounts of variation in the amount of undissolved shoreline harvested as it increased from 1998 to 2006. These variations may be due to harvesters finding particularly high density locations where multiple harvesting events at one location proved worthwhile. It may also indicate multiple boats harvesting the same locations and in later years, with higher quotas, they spread out.

The inclusion of all four calculations of *PDSH* may seem repetitive. Calculating PDSH for all available Subareas gives researchers and managers an idea of how much sea cucumber habitat harvesters are targeting in BC. This is important but different from managers understanding how much of an area harvesters target when they harvest a subarea. The lower values of overall and mean *PDSH* , when calculated for all available Subareas, may hide what managers are more interested in: the amount of harvested shoreline in the targeted Subareas, which is summarized in the other two calculations.

Of the surveyed areas, some transect locations with highest densities do not appear to be fully targeted and this may be creating natural reserves where sea cucumbers are found in high densities, but are not subjected to direct harvest pressure. The quadrat analysis also seems to indicate the existence of natural reserves in the form of unharvested high density areas. These areas may prove to be important as *de facto* reserves, as sea cucumbers are broadcast spawners that likely depend on sufficient density to ensure viable reproductive efforts (Hamel and Mercier 1995). Approximately half of the high density quadrats and high density transects were targeted by fishermen. We are still unsure if harvesters are necessarily targeting high density areas (Section 2).

The overall amount of repeated visits to the same section of coast is low in the sea cucumber industry. In the nine years of data presented here, 85% of the dissolved shoreline harvested was on coastline targeted in one or two years. Yet, the amount of dissolved shoreline has increased from 1998-2006 with the increasing quota. Harvesters could well harvest most of the shoreline available to them along the coast in the long term. Managers would have to depend on natural reserves of high density populations existing long enough to reproduce optimally at least once and that there are enough of these pockets to hedge the uncertainties in success due to geographical challenges or environmental fluctuations.

It is important to note that these data are provided by the harvesters and that it is only as accurate as their ability to record and log harvesting activities. What may appear to be patterns or anomalies, such as the spike in undissolved shoreline harvested in 1999 and the large drop in the following year (Figure 23), may simply be errors in logbook data entries, errors in logbook transfers, or imprecise indications of fishing activity.

These geo-referenced data can certainly yield more information with further analysis and study. Recommendations would include exploring relationships between the abundance of sea cucumbers and physical and oceanographic attributes of the area. A comparison of undissolved shoreline vs. density and an evaluation of trends over time may reveal something of the dynamics of 'hot spots'.

6 Geographical Analysis - Sea Cucumber Habitat Classification

6.1 Background

The provincial government of British Columbia developed a biophysical shore-zone mapping system in 1975 in order to inventory the physical and biological characteristics of the British Columbia shoreline and the intertidal zones (Howes 2001). The information from the inventory is used to support various coastal initiatives such as coastal land use planning, conservation and protection and shoreline habitat modeling. The ShoreZone GIS database was explored to attempt to identify a subset of intertidal or shallow subtidal characteristics that could be related to good sea cucumber habitat, areas with higher linear densities, and potentially popular fishing areas.

6.2 Data Description

Low tide aerial video imagery is the primary source of information for delineating the along-shore physical characteristics of ShoreZone habitat units (Howes et al. 1997). Image resolution is sufficient to resolve objects the size of boulders. An ecologist was present during the flight to record a commentary of observed features. Along-shore features were characterized by habitat and substrate type (shore units). "Biobands" were then identified across the shore unit in the backshore, intertidal, shallow subtidal and deep subtidal zones (Searing and Frith 1995). Typical biota, such as sea urchins or algae types, were defined as indicator species both of expected species communities and of exposure to wind and waves. ShoreZone dataset is structured so that different combinations of data attributes could be used to represent or analyze habitat.

6.3 Analytical Methods

ShoreZone data attributes used in this analysis included shoreline habitat types, substrate composition, bioband algae types, and exposure class (an index of average and maximum wind and wave exposure) (Howes et al. 1997, Searing and Frith 1995).

Shoreline Habitat Type
The range and average of sea cucumber densities, from the Area 7 dive survey in 2006, was summarized for each of the ShoreZone shoreline habitat types in Area 7 to determine if an area with high sea cucumber population densities could be associated with a subset of shoreline habitat types. Examples of shoreline habitat types typical of the Area 7 shoreline include rock cliffs, bedrock ramps and gravel beaches.

Substrate
Substrate types in the ShoreZone dataset, for each shore unit, were compared to substrate observations along the Area 7 2006 dive transects to determine if the ShoreZone substrate type could be used as an indicator of substrate composition observed on the dives, and possibly sea cucumber habitat at depths deeper than the low intertidal zone.

Algae
Algae observations during 2006 dive surveys of Area 7 were compared to the ShoreZone bioband algae classifications to determine if an area of high sea cucumber population density could be associated with particular algae indicator species. Examples of algae types observed on the dive transects include *Agarum spp.*, *Laminaria spp.*, and *Zostera spp.*

Exposure Class
When the ShoreZone database was developed, each shore unit was assigned a category using a ratio of maximum fetch (maximum exposure to wind and waves) and modified effective fetch. The modified effective fetch is calculated from an average of the fetch at the center of the shore unit (perpendicular to the shoreline, called "shore normal") and from the fetch distance at 45 degrees on either side of the shore normal fetch. The direction of maximum fetch may not be at shore normal (Howes et al. 1997, Searing and Frith 1995, Morris and Thuringer 2001). Subsequently, the assignments were reviewed by a marine biologist, who used the bioband observations to change the exposure class, if needed, based on knowledge of the exposure tolerances of the species present (Searing & Frith 1995) (Table 16). Exposure class categories provide an indication of wave exposure for each physical shore unit. For this analysis, the range and average of sea cucumber linear densities in four management areas were summarized by ShoreZone exposure class. A preliminary visual analysis also compared the exposure classes to annual dissolved shoreline harvested (see Section 6.2).

6.4 Results

Habitat type
Initial analysis, using data from the Area 7 survey in 2006, could not find an association of high sea cucumber densities with any subset of the ShoreZone shoreline habitat types. Sea cucumbers were widely distributed, but most of the shoreline types also included dive transects where no sea cucumbers were found. This implies that other factors besides shoreline habitat type may be influencing sea cucumber population densities or presence.

Substrate
It was not feasible to use the ShoreZone substrate classifications to predict substrates in the subtidal zone. This was due to a typical variation in substrates along an entire transect, regardless of the initial, shoreline, composition.

Algae
The most common quadrat algae observation during dive transects was "no algae". On quadrats where algae was observed, algae types were mostly associated with three ShoreZone biobands in the deeper intertidal and shallower subtidal zones (soft brown algae, chocolate brown algae and *Zostera*). Application of this is limited, however. Biologists only added a bioband classification to the ShoreZone data set if species identification could be confidently made from the aerial video (Searing and Frith 1995). Lack of an entry did not necessarily mean the species was not present in the intertidal zone, but rather that it could not be definitely determined, due to shading, glare or some other reason. Because of this, development of a predictive habitat model using the algae biobands was not pursued.

Exposure class
For the exposure class analysis, the study area was expanded to include the Tofino, Trutch/Estevan, and Gil/Gribbell areas. Area 7 dive transects were on semi-protected, protected and very protected shorelines, and Gil/Gribbell only had transects on semi-exposed, semi-protected and protected shorelines. Similar mean densities of sea cucumbers were seen in these latter three classes (Table 16). However, lower mean densities of sea cucumbers were seen in the relatively small number of transects located on exposed shoreline (Tofino and Trutch), and on very protected shorelines at Trutch (Tables 16 and 17).

Fishing Effort
The preliminary visual analysis of the dissolved shoreline harvested and the ShoreZone exposure classes found that fishing effort took place almost entirely from shorelines in the semi-protected and protected exposure classes, with a small amount of fishing effort from semi-exposed shorelines that were in close proximity to semi-protected and protected shorelines (Table 18).

6.5 Discussion

The results suggest that the ShoreZone exposure classes may be useful in providing indications of where, in a Subarea, fishing effort would be focussed. We know from the analysis presented in Section 6 that harvesters do not target the same piece of shoreline year after year. Exposure class could be useful, along with harvest history, in predicting future harvesting locations. Exposure classifications could also be used to refine estimates of harvestable shoreline length in Subareas, as some areas are expected to be avoided and some areas will be preferred. As an example, length of shoreline by exposure class is summarized by Subarea for PFMA 6 (Table 19).

One difficulty in using the ShoreZone dataset in an analysis of dissolved fishing effort is that the ShoreZone shoreline is approximately 15 percent longer than the GIS shoreline layer used by DFO. There are several reasons for this. First, the ShoreZone shoreline was mapped at a finer scale than the DFO shoreline. In addition, the ShoreZone GIS layer includes small islands and islets and estuarine habitats, which the DFO layer often does not. Exclusion of estuarine shoreline from this analysis would reduce the length of the ShoreZone GIS layer to some degree, and might allow better comparison with the DFO GIS layer.

7 General Discussion

Sea cucumbers are difficult creatures to study. Apart from the challenges that result from our inability to age the animals, there appears to be a multitude of factors unrelated to fishing that influence their population dynamics. The ten-year Phase 1 fishery has generated a large quantity of data. This paper contains only a portion of the knowledge that can be gained from it, but sufficient to allow recommendations for a precautionary harvest approach for the British Columbia fishery.

Overall, densities and mean weights of sea cucumbers along the coast of BC appear to be declining in areas open to the fishery, although the decline can often not be directly attributed to harvest intensity. There is considerable variation in the trends in mean density and mean weight that occur in the absence of harvest activity. Other mechanisms which involve the interplay of environmental variability and sea cucumber population dynamics likely play a significant role. The declines in density are consistent with population projections generated from latent productivity modeling and are not unexpected, since the Phase 1 fishery was designed to create a measurable impact on sea cucumber populations that could be evaluated.

The median maximum sustainable harvest rates (MSHR) from the latent productivity model were estimated to be 5.7%, 11.4%, 11.9% and 14.4% of the virgin biomass per year for Laredo, Jervis, Tolmie and Zeballos experimental fishery areas, respectively. With the exception of Laredo, these compare fairly closely with the best-fit estimates of the proportion of unfished biomass recommended by Bradbury et al. (1996) of 12-14% based on the Schaefer surplus production model, and with results of a modified Caddy's surplus production model (Woodby et al. 1993) of 12.8% of unfished biomass. To be precautionary, and in light of the uncertainty in the data, managers may decide to choose from removal rate options at the lower one percentile of model results of MSHR, which are 3.5%, 6.7%, 9.4%, 10.3% for Laredo, Jervis, Tolmie and Zeballos, respectively. If it is accepted that the Laredo EFA represents an area that would not typically be chosen for harvest, and that such areas would not be considered for the fishery (or fished differently), a harvest rate of 6.7% of virgin biomass appears to be sustainable and is considered low risk for commercially-viable areas of average, or better, productivity. When combined with conservative estimates of biomass (lower 90% confidence interval of estimated mean density), and considering that only the shallow portion of the total sea cucumber population is estimated, this option is even more precautionary.

For all EFAs except Laredo, latent productivity increased with a decrease in relative biomass, and maximum latent productivity occurred at some point beyond the range of available data ($x_{truncate}$, or lower abundance). Values of $x_{truncate}$ may be used as a basis to establish a limit reference point (LRP), the point that delineates the Cautious and Critical stock status zones (DFO, 2006). These values are the lowest relative biomass to which the population declined in each of the EFAs and, from modeling results, we can claim that we have witnessed the system's recovery from this state. The lowest relative abundance (median estimate using spatial density) that was reached in the EFAs ranged from 28% to 46% of virgin biomass. A conservative LRP of 50% of B_0 could be adopted for the sea cucumber fishery, pending further evaluation of results from on-going studies. This reference point is more conservative than the 40% B_{MSY} recommended for use in fisheries that lack stock assessment information (DFO 2006) because it is a higher threshold (50% vs 40%), and because B_{MSY} is generally understood to be less that B_0.

The population projection output from the latent productivity model may be useful for managers to develop an Upper Stock Reference Point (USR) for sea cucumber populations in British Columbia. This reference point marks the boundary between the Healthy and Cautious stock status zones (DFO 2006). At a 6.7% harvest rate, biomass in the three commercially-feasible EFAs (Tolmie, Jervis and Zeballos) is expected to stabilize at approximately 60% to 80% of B_0. A relative stock abundance in that range could be considered for the USR, along with the social and economic objectives for the fishery. Relative stock status in the surveyed commercially-fished areas ranged from 90% to 77% of initial biomass estimates. (Note, however, that initial biomass estimates are likely lower than virgin levels because the areas had been fished prior to the Phase 1 study period.) For those surveyed areas, at least, the current stock status appears to be within the Healthy zone.

An additional measure that managers may find useful is a lower density limit. Model results from the Laredo EFA and from earlier work on rotational harvest strategies (Humble et al. 2007) suggests that low density sea cucumber populations have low stock resilience and need either to be fished at a lower rate or a longer rotation. The lowest modelled virgin biomass density estimates from Jervis Inlet EFA, which appears to be sustainable at 6.7%, are 1.5 kg per metre of shoreline or 0.02 kg per square metre. Fishery managers may find this virgin density limit a useful guide for determining whether an area should be opened to the commercial fishery or to set a more conservative harvest regime. A minimum density that could be used as an alternative to 50% B_0 LRP could be 2.5 sea cucumbers per metre of shoreline, which is 50% of the baseline density estimate currently applied to unsurveyed areas.

The data collected from Experimental Fishery Areas have proven to be highly valuable for examining the response of sea cucumber populations to a range of harvest intensities. The nine-year time-series of data was likely the minimum that would yield meaningful results. The lag in response time for sea cucumber populations subjected to varying harvest rates is evidenced by the changing model results with successive years of data. Therefore, continuing with experimental harvest and monitoring in at least some of the EFAs will hopefully allow the results to reach equilibrium, and add significantly to the

value of the experiments. Additional years in the time-series may provide new lower bounds of recoverable populations, and thus an evaluation of the LRP.

Approximately half of the high density transects and high density quadrats in the open areas were not harvested at all during the 10-year interval of this Phase 1 fishery simply because the amount of the available shoreline targeted by harvesters to fill their annual quotas is currently relatively small. Harvesters appear to change their harvest locations annually, and therefore all high-density locations may eventually be visited. Currently, the natural harvesting cycle appears to be sufficiently long to ensure that the high-density populations can spawn successfully. It should be recognized, however, that an increase in quota would increase the extent of shoreline targeted by harvesters, resulting in fewer natural spawning reserves or a shorter cycle of harvest within a given area. It would be prudent, at this stage of fishery development, to establish a network of permanent no-harvest reserves in commercial fishing areas. Not only would these reserves function to augment the *de facto* reserves and enhance the exploited populations, the closures would also provide the opportunity to collect baseline data on virgin population density estimates that can be used in conjunction with surveys in comparable harvested areas (Schroeter et al. 2001). The size of the no-harvest reserves should be large enough to indicate trends in the virgin populations and provide the appropriate level of accuracy, yet not be too onerous to survey. At a sampling intensity of one transect per two km of shoreline, as suggested in Section 2, a no-harvest reserve of 30-35 km of shoreline could be surveyed in one or two days and provide a sample size of approximately 15 transects. This is considered statistically adequate and logistically feasible.

There is a desire among harvesters to return to a rotational harvest, targeting different areas along the coast of BC in different years, with initially lower annual harvest rates. This juncture in the fishery would be an opportune time to make some changes, as there are both conservation and logistical advantages in rotational harvesting. Simulation modeling of sea cucumber populations (Humble et al. 2007) concluded that rotational harvest at a fixed rotation period of three or more years results in higher average animal weight, higher spawning biomass and higher yield than does an annual harvest strategy. The undisturbed years between harvests would allow sea cucumbers to aggregate, which is suspected to occur in this broadcast spawner but yet to be reported, and to spawn with a greater probability of fertilization success. Ensuring high-density shallow populations in some areas may also be important, as there is evidence that spawning cues from chemicals emitted in mucus by shallow populations of *Cucumaria frondosa* in response to daylength or temperature may trigger deep populations into spawning (Hamel and Mercier 1999).

Logistical advantages of a rotational harvest strategy for the sea cucumber industry are also apparent. In switching to rotational harvesting, harvest effort would be concentrated in a smaller area, requiring less travel and reduced overhead costs. Fewer landing ports for catch validations would need to be staffed in a season, also reducing costs. These reductions in overhead costs would make the fishery more profitable with small quotas. Additionally, in a rotational harvest there is more control by managers over the location and timing of harvesting. This allows surveys, observations, and potential changes to occur in a smaller controlled area, making adaptive resource management more practical and applicable.

Biomass calculations for the establishment of quotas in the commercial fishery currently incorporate the most recent data on mean weight of sea cucumbers in the area, which may be dated by as much as four years (the current sampling interval). The four-year cycle makes short-term trends in the population impossible to observe and incorporate into stock assessment. Current trials are underway to improve weight estimations by collecting biosamples of sea cucumbers from open areas prior to harvesting.

There are still gaps in our knowledge of the biology and distribution of these soft-bodied benthic broadcast spawners. More research focusing on the life history, population dynamics and depth distribution of the giant red sea cucumber is needed to better understand the effects of harvesting and environmental variability on productivity and to predict how changes in management will affect sea cucumber populations. This knowledge may become increasingly important as weather patterns and the state of the ocean continues to change. An area in need of investigation to improve sea cucumber stock assessment is the extent to which harvested populations are replenished through bathymetric migration. Initial plans are underway to investigate this with Remotely Operated Vehicle (ROV) surveys in deep and shallow water in conjunction with SCUBA surveys. In addition, there is a clear need for data on recruitment strength and variability, since these are important parameters for assessing the productivity of sea cucumber populations. The installation of juvenile collectors to establish a time-series on recruitment strength and allow analysis of trends in relation to climate or habitat variables independent of fishing impacts should be undertaken. By conducting annual counts of these collectors, insight can be gained into the magnitude of recruitment fluctuation between areas and years, and correlations between density, size estimates and recruitment levels can be explored.

Further examination of the BC provincial biophysical shore-zone inventory is warranted to look for additional associations to sea cucumber abundance and productivity and to assist in selecting new areas in BC to open, areas to avoid or in choosing appropriate target harvest rates. This paper, at the very least, was able to associate sea cucumber density with exposure class and found that lower mean densities were seen in exposed and very exposed shoreline. The extents of shoreline that are classified as exposed or very exposed should be excluded from calculations of biomass for quota recommendations.

8 Recommendations

1. Expand the sea cucumber commercial fishery to other areas along the British Columbia coast using annual harvest rate ranging from 3.5% to 10.3% of estimated current biomass. If unproductive, low-density areas are avoided, a conservative annual harvest rate of 6.7% is recommended.
2. Adopt a conservative Limit Reference Point of 50% B_0, and consider an Upper Stock Reference Point in the range of 60% to 80% B_0.
3. Continue surveying and fishing the experimental fishery areas, or a subset, as resources permit. Extending the existing 10-year time-series with additional years of data is expected to provide extremely valuable results.

4. Design a network of designated no-take zones in commercial fishing areas, to include a range of different densities or carrying capacities. These areas would be surveyed along with the harvested areas to assess and compare changes in the harvested and un-harvested areas and to provide a time-series of estimates of virgin population size.
5. Eliminate areas of high exposure, low productivity or unfishable shoreline from estimates of fishable biomass.

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Table 1. History of management actions in the sea cucumber (*Parastichopus californicus)* fishery.

YEAR	Management measure	Details
1971	Not regulated	First commercial harvest of sea cucumbers
1980	Licences	Arbitrary management regime
1986	Licences	Area closures and arbitrary area quotas
1989	Licences	Quota reduction prompted by declining CPUE
1991	Licence limitations (78)	Limit of 78 licences
1992	Licence limitation (84); Split weight used to allocate quota	Limit of 84 licences. Setting and monitoring quotas based on split weight (logbook generally reported round weight prior to 1991)
1993	Rotational fishery introduced	2-year rotation period in the northern coastal area, 3 year rotation period in the southern coastal area; Quota reduction because of declining CPUE
1994		Quota reduction prompted by declining CPUE
1995	Individual quotas, 85 licences	Equal IQ for 85 licences. Catch monitoring and validation program required. Area closures
1996	4 licensing areas	Area licensing: West Coast Vancouver Island, East Coast Vancouver Is., Prince Rupert & Central Coast
1997	Rotational fishery discontinued. New Adaptive Management Strategy. Estimated density.	Fishery restricted to 25% of the coast. 85 licences. Catch monitoring and validation program required. Four licensing areas (WCVI, ECVI, PR & CC). Detailed harvest information and harvest maps required. TAC determined using density estimates from Alaska (2.5 c/m-sh).
1998 to 2002	Surveys	Survey densities used to calculate quotas in surveyed areas.
2003	New baseline density	A new baseline density of 5.08 c/m-sh, derived from field surveys, used to calculate quotas for most of BC coastline (except areas known to be unfavourable to sea cucumbers and surveyed areas).

Table 2. Density survey and biosample collection schedule from 1998-2007 in the six surveyed open harvesting areas (Area 7, Fitz Hugh Sound, Trutch, Gil/Gribbell, Area 12 Inlets, Tofino). S=Surveyed in that year, B=Biosampled in that year.

Survey Area	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Area 7	S/B				S/B				S/B	
Fitz Hugh Sound					S/B				S/B	
Trutch				S/B				S/B		
Gil/Gribbell		S/B				S/B				S/B
Area 12 Inlets			S/B				S/B			
Tofino				S/B				S/B		

Table 3. Sea cucumber landings (kg round weight), by survey location and year, from 1985 to 2006. Values in bold represent commercial harvest that occurred during the four years prior to the first survey in the area.

YEAR	AREA 7	Gil Gribbell	AREA 12	TOFINO	TRUTCH	FITZ HUGH
1985	0	0	0	19416	0	0
1987	125731	0	0	15938	0	0
1988	49671	0	0	266154	0	9110
1989	116309	0	0	62538	0	0
1990	80439	0	6216	85108	0	0
1991	168209	0	0	0	9212	0
1992	5553	26916	46285	80932	75999	67361
1993	0	47909	0	0	23732	0
1994	**0**	0	0	24952	0	0
1995	**0**	**0**	4644	64207	0	144987
1996	**256440**	**98973**	**0**	0	5930	0
1997	**46684**	**75180**	**24515**	**45240**	**43812**	129363
1998	97417	**80292**	**20139**	**44675**	**0**	**110632**
1999	119002	230211	**22246**	**44588**	**29825**	**57603**
2000	158176	238444	73898	**44057**	**8872**	**58257**
2001	127545	216322	75606	62151	50482	**67100**
2002	121298	231965	59084	53391	27172	110621
2003	143201	222071	71696	66955	110355	163649
2004	148693	183871	82559	66878	81055	87273
2005	188759	197986	70599	56687	90465	110433
2006	168200	195667	75926	54487	130522	85867
TOTAL	2121327	2045807	633413	1158354	687433	1202256
Total for four pre-survey years	**303124**	**254445**	**66900**	**178560**	**82509**	**293592**

Table 4. Results of pairwise comparisons of linear densities from Gil/Gribbell survey (Subareas pooled), showing a comparison of the untruncated vs. truncated data sets. P-values in bold indicate instances where the datasets differ in significance for the comparison.

A) Untruncated dataset

Gil/Gribbell - Linear Density (sea cucumbers per metre)												
	1999				2003				2007			
Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
			Lower	Upper			Lower	Upper			Lower	Upper
233	19.877	1.202	18.199	22.066	17.377	0.910	15.761	18.697	16.538	0.945	14.962	18.004

Gil/Gribbell - Change in Linear Density (sea cucumbers per metre)												
	1999 to 2003				2003 to 2007				1999 to 2007			
Number of Transects	Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?	
			Classical	Bootstrap			Classical	Bootstrap			Classical	Bootstrap
233	-2.500	1.252	**0.023**	**0.019**	-0.839	0.817	0.153	0.157	-3.339	1.250	**0.004**	**0.000**

B) Truncated dataset.

Gil/Gribbell - Linear Density (sea cucumbers per metre)												
	1999				2003				2007			
Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
			Lower	Upper			Lower	Upper			Lower	Upper
233	15.269	0.928	13.769	16.898	14.361	0.813	13.089	15.717	13.768	0.828	12.547	15.173

Gil/Gribbell - Change in Linear Density (sea cucumbers per metre)												
	1999 to 2003				2003 to 2007				1999 to 2007			
Number of Transects	Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?	
			Classical	Bootstrap			Classical	Bootstrap			Classical	Bootstrap
233	-0.974	0.868	0.131	0.106	-0.533	0.659	0.210	0.217	-1.501	0.848	**0.039**	0.053

Table 5. Results of pairwise analysis of truncated linear and spatial density data for Area 7, with mean density estimate, standard error and 90% confidence bounds for each year surveyed, by Subarea and pooled (first and third panel) and the change in linear and spatial density between each year surveyed and the significance of the negative mean change (second and fourth panel).

Area 7 - Linear Density (sea cucumbers per metre)

Sub-Area	Number of Transects	1998				2002				2006			
		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
				Lower	Upper			Lower	Upper			Lower	Upper
15	66	5.697	0.774	4.557	7.089	6.841	0.853	5.640	8.203	5.027	0.853	4.012	6.377
17	104	10.731	1.028	9.188	12.608	9.464	0.957	7.927	11.087	10.214	0.957	8.819	11.886
30	18	16.097	4.238	10.740	24.949	13.306	3.801	8.805	21.274	11.375	3.801	7.774	16.743
Pooled	188	9.477	0.778	8.307	10.824	8.914	0.716	7.827	10.313	8.513	0.716	7.515	9.621

Area 7 - Change in Linear Density (sea cucumbers per metre)

Sub-Area	Number of Transects	1998 to 2002				2002 to 2006				1998 to 2006			
		Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?	
				Classical	Bootstrap			Classical	Bootstrap			Classical	Bootstrap
15	66	1.144	0.596	0.970	0.975	-1.814	0.694	**0.006**	**0.000**	-0.670	0.626	0.144	0.125
17	104	-1.192	0.678	**0.041**	**0.043**	0.750	0.573	0.903	0.878	-0.433	0.819	0.299	0.277
30	18	-2.792	1.845	0.074	0.054	-1.931	1.900	0.162	0.121	-4.722	1.952	**0.014**	**0.000**
Pooled	188	-0.525	0.472	0.133	0.123	-0.401	0.446	0.185	0.168	-0.927	0.542	**0.044**	0.061

Area 7 - Spatial Density (sea cucumbers per metre-squared)

Sub-Area	Number of Transects	1998				2002				2006			
		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
				Lower	Upper			Lower	Upper			Lower	Upper
15	66	0.161	0.023	0.125	0.200	0.193	0.026	0.155	0.244	0.142	0.026	0.113	0.184
17	104	0.260	0.021	0.227	0.297	0.231	0.021	0.196	0.266	0.249	0.021	0.216	0.284
30	18	0.417	0.061	0.328	0.529	0.345	0.064	0.251	0.456	0.295	0.064	0.223	0.361
Pooled	188	0.243	0.017	0.217	0.272	0.230	0.017	0.205	0.260	0.219	0.017	0.197	0.246

Area 7 - Change in Spatial Density (sea cucumbers per metre-squared)

Sub-Area	Number of Transects	1998 to 2002				2002 to 2006				1998 to 2006			
		Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?	
				Classical	Bootstrap			Classical	Bootstrap			Classical	Bootstrap
15	66	0.032	0.017	0.970	0.966	-0.051	0.020	**0.005**	**0.000**	-0.019	0.018	0.144	0.107
17	104	-0.029	0.016	**0.039**	**0.045**	0.018	0.014	0.902	0.907	-0.010	0.020	0.298	0.315
30	18	-0.072	0.045	0.063	0.063	-0.050	0.047	0.149	0.120	-0.122	0.039	**0.003**	**0.000**
Pooled	188	-0.013	0.012	0.132	0.140	-0.010	0.011	0.184	0.152	-0.024	0.014	**0.042**	**0.032**

Table 6. Results of pairwise analysis of truncated spatial density data from Gil/Gribbell, Trutch, Fitz Hugh Sound, Area 12 and Tofino surveys, with mean density estimate, standard error and 90% confidence bounds for each year surveyed, by Subarea and pooled (first panel) and the change in spatial density between each year surveyed and the significance of the negative mean change (second panel).

a) Gil/Gribbell

Gil/Gribbell - Spatial Density (sea cucumbers per metre-squared)													
		1999				2003				2007			
Sub-Area	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
				Lower	Upper			Lower	Upper			Lower	Upper
3	73	0.328	0.037	0.268	0.388	0.403	0.054	0.322	0.507	0.403	0.056	0.309	0.489
5 and 27	94	0.389	0.032	0.341	0.442	0.413	0.032	0.367	0.472	0.353	0.030	0.307	0.410
6	39	0.800	0.067	0.691	0.903	0.554	0.064	0.455	0.661	0.576	0.079	0.460	0.715
7	12	0.860	0.119	0.669	1.058	0.504	0.076	0.391	0.631	0.633	0.115	0.457	0.815
28	8	0.426	0.061	0.321	0.511	0.432	0.113	0.257	0.606	0.413	0.080	0.275	0.526
Pooled	233	0.472	0.027	0.432	0.519	0.442	0.025	0.403	0.484	0.425	0.027	0.382	0.472

Gil/Gribbell - Change in Spatial Density (sea cucumbers per metre-squared)													
		1999 to 2003				2003 to 2007				1999 to 2007			
Sub-Area	Number of Transects	Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?		Estimate	Standard error	p-value: Is Mean Change Negative?	
				Classical	Bootstrap			Classical	Bootstrap			Classical	Bootstrap
3	73	0.075	0.054	0.915	0.941	0.000	0.043	0.503	0.484	0.075	0.056	0.909	0.925
5 and 27	94	0.024	0.031	0.775	0.779	-0.059	0.025	0.009	0.007	-0.035	0.028	0.107	0.090
6	39	-0.246	0.074	0.001	0.000	0.022	0.060	0.643	0.668	-0.224	0.070	0.001	0.000
7	12	-0.356	0.135	0.012	0.000	0.129	0.083	0.925	0.956	-0.227	0.154	0.084	0.081
28	8	0.006	0.098	0.525	0.533	-0.019	0.080	0.409	0.425	-0.013	0.073	0.433	0.429
Pooled	233	-0.030	0.027	0.130	0.146	-0.016	0.020	0.209	0.207	-0.046	0.026	0.037	0.043

Table 6, cont'd.

b) Trutch

Trutch - Spatial Density (sea cucumbers per metre)										Fitz Hugh - Change in Spatial Density (sea cucumbers per metre-squared)			
		2002				2006				2002 to 2006			
Sub-Area	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?	
				Lower	Upper			Lower	Upper			Classical	Bootstrap
Pooled	136	0.088	0.013	0.070	0.112	0.078	0.011	0.061	0.097	-0.011	0.009	0.114	0.126

c) Fitz Hugh Sound

Fitz Hugh - Spatial Density (sea cucumbers per metre)										Fitz Hugh - Change in Spatial Density (sea cucumbers per metre-squared)			
		2002				2006				2002 to 2006			
Sub-Area	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?	
				Lower	Upper			Lower	Upper			Classical	Bootstrap
3	8	0.101	0.081	0.022	0.328	0.063	0.040	0.016	0.142	-0.039	0.069	0.298	0.245
3 and 4	122	0.273	0.021	0.237	0.306	0.201	0.016	0.178	0.232	-0.072	0.017	**0.000**	**0.000**
4	114	0.284	0.021	0.251	0.321	0.209	0.017	0.185	0.241	-0.074	0.018	**0.000**	**0.000**
5	23	0.539	0.055	0.461	0.635	0.413	0.056	0.332	0.514	-0.126	0.074	0.051	**0.028**
6	12	0.804	0.140	0.616	1.064	0.828	0.067	0.736	0.951	0.024	0.175	0.552	0.522
16	37	0.226	0.030	0.182	0.275	0.157	0.019	0.125	0.186	-0.070	0.022	**0.002**	**0.000**
Pooled	194	0.308	0.022	0.274	0.349	0.238	0.017	0.207	0.263	-0.071	0.016	**0.000**	**0.000**

Table 6, cont'd.

d) Area 12

Area 12 - Spatial Density (sea cucumbers per metre)										Area 12 - Change in Spatial Density (sea cucumbers per metre-squared)			
		2000				2004				2000 to 2004			
Sub-Area	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?	
				Lower	Upper			Lower	Upper			Classical	Bootstrap
40	63	0.234	0.032	0.188	0.296	0.136	0.019	0.107	0.172	-0.098	0.023	**0.000**	**0.000**
41	66	0.159	0.024	0.119	0.196	0.148	0.024	0.115	0.190	-0.011	0.017	0.259	0.242
Pooled	129	0.187	0.020	0.153	0.219	0.144	0.016	0.117	0.171	-0.043	0.014	**0.002**	**0.000**

e)Tofino

Tofino - Spatial Density (sea cucumbers per metre)										Tofino - Change in Spatial Density (sea cucumbers per metre-squared)			
		2001				2005				2001 to 2005			
Sub-Area	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?	
				Lower	Upper			Lower	Upper			Classical	Bootstrap
4	14	0.140	0.022	0.113	0.191	0.164	0.032	0.100	0.207	0.025	0.027	0.808	0.855
5	26	0.136	0.021	0.102	0.167	0.151	0.025	0.113	0.196	0.015	0.018	0.786	0.810
6	13	0.064	0.030	0.027	0.131	0.039	0.023	0.015	0.105	-0.025	0.022	0.138	**0.035**
7	27	0.138	0.016	0.103	0.165	0.065	0.028	0.030	0.119	-0.073	0.033	**0.017**	**0.009**
10	31	0.050	0.018	0.030	0.094	0.050	0.019	0.028	0.097	0.001	0.008	0.531	0.533
14	12	0.136	0.027	0.086	0.173	0.085	0.022	0.053	0.128	-0.051	0.021	**0.018**	**0.010**
Pooled	123	0.102	0.011	0.086	0.122	0.081	0.012	0.061	0.102	-0.022	0.015	0.080	**0.032**

Table 7. Results of analysis of survey data to evaluate whether transects that had been harvested in the recent past showed more of a decline in density than transects that were unharvested, using two different criteria (transects were fished in the previous year and transects fished three times during the five-year period prior to the last survey).

a) Gil/Gribbell

Gil Gribbell - Spatial Density (sea cucumbers per metre-squared)									
		1999				2007			
Harvested in 2006	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
				Lower	Upper			Lower	Upper
No	174	0.483	0.031	0.433	0.537	0.476	0.032	0.422	0.529
Yes	60	0.447	0.052	0.363	0.529	0.314	0.039	0.257	0.386

Gil Gribbell - Change in Spatial Density (sea cucumbers per metre-squared)				
1999 to 2007				
Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero Harvest?
		Classical	Bootstrap	
-0.008	0.033	0.401	0.394	0.470
-0.134	0.040	0.001	0.000	0.005

Gil Gribbell - Spatial Density (sea cucumbers per metre-squared)									
		1999				2007			
Harvested three times between 2002 and 2006	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
				Lower	Upper			Lower	Upper
No	197	0.483	0.031	0.440	0.544	0.462	0.031	0.414	0.514
Yes	37	0.424	0.054	0.337	0.516	0.274	0.044	0.216	0.371

Gil Gribbell - Change in Spatial Density (sea cucumbers per metre-squared)				
1999 to 2007				
Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero Harvest?
		Classical	Bootstrap	
-0.022	0.030	0.231	0.217	0.554
-0.150	0.043	0.001	0.000	0.013

b) Trutch. Note: There were only 5 transects that were harvested in at least 3 of the last 5 years. Sample size is too small to use bootstrapping to generate confidence bounds and p-values.

Trutch - Spatial Density (sea cucumbers per metre-squared)									
		2001				2005			
Harvested in 2004	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
				Lower	Upper			Lower	Upper
No	50	0.128	0.022	0.096	0.167	0.091	0.016	0.067	0.120
Yes	10	0.064	0.036	0.020	0.142	0.080	0.038	0.033	0.168

Trutch - Change in Spatial Density (sea cucumbers per metre-squared)				
2001 to 2005				
Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero Harvest?
		Classical	Bootstrap	
-0.036	0.016	0.014	0.006	0.471
0.016	0.022	0.757	0.775	0.958

Table 7 cont'd.

c) Area 7

Area 7 - Spatial Density (sea cucumbers per metre-squared)										Area 7 - Change in Spatial Density (sea cucumbers per metre-sq)				
		1998				2006				1998 to 2006				
Harvested in 2005	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero Harvest?
				Lower	Upper			Lower	Upper			Classical	Bootstrap	
No	131	0.212	0.021	0.184	0.253	0.213	0.019	0.183	0.249	0.001	0.016	0.515	0.477	0.506
Yes	58	0.300	0.028	0.248	0.347	0.232	0.025	0.191	0.272	-0.068	0.025	0.004	0.000	0.005

Area 7 - Spatial Density (sea cucumbers per metre-squared)										Area 7 - Change in Spatial Density (sea cucumbers per metre-sq)				
		1998				2006				1998 to 2006				
Harvested three times between 2001 and 2005	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero Harvest?
				Lower	Upper			Lower	Upper			Classical	Bootstrap	
No	163	0.225	0.019	0.196	0.258	0.219	0.017	0.193	0.247	-0.006	0.014	0.343	0.313	0.470
Yes	26	0.337	0.035	0.282	0.397	0.221	0.033	0.167	0.274	-0.116	0.043	0.006	0.000	0.005

d) Fitz Hugh Sound

Fitz Hugh - Spatial Density (sea cucumbers per metre-squared)										Fitz Hugh - Change in Spatial Density (sea cucumbers per metre-squared)				
		2002				2006				2002 to 2006				
Harvested in 2005	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero harvest?
				Lower	Upper			Lower	Upper			Classical	Bootstrap	
No	162	0.304	0.026	0.268	0.351	0.245	0.020	0.216	0.281	-0.059	0.018	0.000	0.000	0.488
Yes	32	0.313	0.039	0.249	0.377	0.209	0.024	0.172	0.260	-0.104	0.033	0.002	0.000	0.135

Fitz Hugh - Spatial Density (sea cucumbers per metre-squared)										Fitz Hugh - Change in Spatial Density (sea cucumbers per metre-squared)				
		2002				2006				2002 to 2006				
Harvested three times between 2001 and 2005	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero harvest?
				Lower	Upper			Lower	Upper			Classical	Bootstrap	
No	175	0.315	0.024	0.280	0.361	0.249	0.019	0.220	0.282	-0.065	0.017	0.000	0.000	0.528
Yes	19	0.260	0.050	0.195	0.356	0.165	0.017	0.137	0.189	-0.095	0.044	0.023	0.000	0.257

Table 7, cont'd.

e) Area 12 Inlets. Note: There were only 5 transects that were harvested at least 3 times in the last five years. Sample size is too small to use bootstrapping to generate confidence bounds and p-values.

		Area 12 - Spatial Density (sea cucumbers per metre-squared)								Area 12 - Change in Spatial Density (sea cucumbers per metre-sq)				
		2000				2004				2000 to 2004				
Harvested in 2003	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap) Lower	Upper	Estimate	Standard error	90% Confidence Bound (bootstrap) Lower	Upper	Estimate	Standard error	p-value: Is Mean Change Negative? Classical	Bootstrap	p-value: Is decline more than for zero Harvest?
No	116	0.185	0.021	0.149	0.220	0.146	0.018	0.117	0.176	-0.039	0.015	0.006	0.012	0.506
Yes	12	0.195	0.048	0.121	0.272	0.131	0.031	0.083	0.184	-0.064	0.043	0.081	0.000	0.280

f) Tofino

		Tofino - Spatial Density (sea cucumbers per metre-squared)								Tofino - Change in Spatial Density (sea cucumbers per metre-squared)				
		2001				2005				2001 to 2005				
Harvested in 2004	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap) Lower	Upper	Estimate	Standard error	90% Confidence Bound (bootstrap) Lower	Upper	Estimate	Standard error	p-value: Is Mean Change Negative? Classical	Bootstrap	p-value: Is decline more than for zero Harvest?
No	101	0.095	0.013	0.077	0.119	0.070	0.013	0.050	0.090	-0.025	0.017	0.066	0.022	0.490
Yes	16	0.140	0.033	0.086	0.194	0.183	0.024	0.141	0.219	0.043	0.033	0.898	0.908	0.833

		Tofino - Spatial Density (sea cucumbers per metre-squared)								Tofino - Change in Spatial Density (sea cucumbers per metre-squared)				
		2001				2005				2001 to 2005				
Harvested three times between 2000 and 2004	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap) Lower	Upper	Estimate	Standard error	90% Confidence Bound (bootstrap) Lower	Upper	Estimate	Standard error	p-value: Is Mean Change Negative? Classical	Bootstrap	p-value: Is decline more than for zero Harvest?
No	110	0.098	0.012	0.078	0.117	0.077	0.013	0.059	0.099	-0.021	0.016	0.102	0.050	0.507
Yes	7	0.125	0.050	0.057	0.217	0.147	0.049	0.071	0.220	0.022	0.026	0.787	0.805	0.897

Table 8. The years that density surveys were conducted and biosamples collected in the four Experimental Fishery Areas (Laredo Inlet, Tolmie Channel, Jervis Inlet and Zeballos). S=Surveyed in that year; B=Biosampled in that year.

EFA	Site	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Lardeo Inlet	0	S/B	S/B	S/B	S/B	B	S/B	B	S/B	B	S/B
	2	S	S/B	B	B	B	S/B	B	B	B	S/B
	4	S/B	S/B	B	B	B	S/B	B	B	B	S/B
	8	S/B	S/B	S/B	S/B	B	S/B	B	S/B	B	S/B
	16	S/B	S/B	S/B	S/B	B	S/B	B	S/B	B	S/B
Tolmie Channel	0	B	S/B	S/B	S/B	B	S/B	B	S/B	B	S/B
	2	B	S/B	B	B	B	S/B	B	B	B	S/B
	4	B	S/B	B	B	B	S/B	B	B	B	S/B
	8	B	S/B	B	S/B	B	S/B	B	S/B	B	S/B
	16	B	S/B	B	S/B	B	S/B	B	S/B	B	S/B
Jervis Inlet	0		S/B	B	S/B	B	S/B	B	S/B	B	S/B
	2		S/B	B	B	B	S/B	B	B	B	S/B
	4		S/B	B	B	B	S/B	B	B	B	S/B
	8		S/B	B	S/B	B	S/B	B	S/B	B	S/B
	16		S/B	B	S/B	B	S/B	B	S/B	B	S/B
Zeballos	0		S/B	B	S/B	B	S/B	B	S/B	B	S/B
	2		S/B	B	B	B	S/B	B	B	B	S/B
	4		S/B	B	B	B	S/B	B	B	B	S/B
	8		S/B	B	S/B	B	S/B	B	S/B	B	S/B
	16		S/B	B	S/B	B	S/B	B	S/B	B	S/B

Table 9. Spatial density estimates for experimental harvesting sites in a.) Laredo Inlet and b.) Tolmie Channel for 1998 and 2007, c) Jervis Inlet and d) Zeballos Inlet for 1999 and 2007. Estimated (mean) change in density for each transect is tested by classical and bootstrapping methods; changes in harvest site density are tested against changes in Site 0 density, p-values less than 0.05 indicate the decline in the harvest site is greater than that observed in Site 0. The maximum number of transects were used to estimate mean density in the first and final surveys: in some cases, fewer transects were surveyed in the final survey than in the initial survey. This resulted in some cases where the difference of the means did not equal the mean of the differences.

a.)

Laredo Inlet - Spatial Density (sea cucumbers per metre)										Laredo Inlet - Change in Spatial Density (sea cucumbers per metre-squared)				
		1998				2007				1998 to 2007				
Harvest Rate(%)	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero harvest?
				Lower	Upper			Lower	Upper			Classical	Bootstrap	
0	16	0.070	0.021	0.043	0.113	0.060	0.018	0.034	0.091	-0.010	0.023	0.334	0.309	0.510
2	16	0.046	0.017	0.026	0.088	0.039	0.016	0.020	0.071	-0.008	0.013	0.280	0.315	0.308
4	15	0.094	0.018	0.072	0.128	0.157	0.031	0.121	0.224	0.062	0.028	0.980	1.000	0.946
8	15	0.073	0.035	0.033	0.164	0.022	0.008	0.011	0.035	-0.051	0.029	0.051	0.000	0.103
16	16	0.122	0.018	0.096	0.156	0.083	0.022	0.052	0.122	-0.039	0.024	0.063	0.060	0.195

b.)

Tolmie Channel - Spatial Density (sea cucumbers per metre)										Tolmie Channel - Change in Spatial Density (sea cucumbers per metre-squared)				
		1998				2007				1998 to 2007				
Harvest Rate(%)	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero harvest?
				Lower	Upper			Lower	Upper			Classical	Bootstrap	
0	15	0.535	0.099	0.398	0.714	0.717	0.087	0.567	0.841	0.182	0.110	0.940	0.956	0.529
2	22	0.467	0.071	0.370	0.598	0.549	0.051	0.474	0.633	0.048	0.061	0.779	0.761	0.114
4	15	0.383	0.080	0.264	0.539	0.306	0.066	0.215	0.433	-0.077	0.088	0.198	0.217	0.025
8	15	0.363	0.079	0.251	0.496	0.168	0.043	0.116	0.267	-0.194	0.093	0.028	0.012	0.025
16	20	0.391	0.082	0.268	0.532	0.259	0.055	0.193	0.388	-0.132	0.104	0.110	0.086	0.015

Table 9 cont'd.

c.)

Jervis Inlet - Spatial Density (sea cucumbers per metre)										
		1999				2007				
Harvest Rate(%)	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)		
				Lower	Upper			Lower	Upper	
0	25	0.156	0.024	0.126	0.209	0.174	0.034	0.127	0.235	
2	26	0.153	0.034	0.105	0.218	0.079	0.013	0.059	0.100	
4	15	0.387	0.094	0.222	0.529	0.288	0.079	0.181	0.449	
8	26	0.049	0.018	0.023	0.082	0.043	0.012	0.025	0.065	
16	16	0.168	0.037	0.110	0.231	0.043	0.009	0.029	0.060	

Jervis Inlet - Change in Spatial Density (sea cucumbers per metre-squared)				
1999 to 2007				
Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero harvest?
		Classical	Bootstrap	
0.018	0.029	0.727	0.758	0.511
-0.076	0.030	**0.009**	**0.000**	0.095
-0.099	0.077	0.110	0.094	0.170
-0.014	0.013	0.146	0.107	0.466
-0.125	0.037	**0.002**	**0.000**	0.054

d.)

Zeballos - Linear Density (sea cucumbers per metre)									
		1999				2007			
Harvest Rate(%)	Number of Transects	Estimate	Standard error	90% Confidence Bound (bootstrap)		Estimate	Standard error	90% Confidence Bound (bootstrap)	
				Lower	Upper			Lower	Upper
0	15	2.783	0.744	1.758	4.169	4.650	0.885	3.575	6.397
2	15	4.417	0.894	3.150	6.033	3.600	0.822	2.408	5.004
4	15	3.733	1.036	2.392	5.920	3.950	0.677	3.011	5.152
8	15	3.883	0.998	2.542	5.759	4.083	1.234	2.576	6.792
16	15	4.000	0.946	2.753	5.833	2.300	0.404	1.708	2.983

Zeballos - Change in Linear Density (sea cucumbers per metre)				
1999 to 2007				
Estimate	Standard error	p-value: Is Mean Change Negative?		p-value: Is decline more than for zero harvest?
		Classical	Bootstrap	
1.867	0.601	0.996	1.000	0.495
-0.817	0.611	0.101	0.069	0.005
0.217	0.902	0.593	0.635	0.055
0.200	1.200	0.565	0.620	0.118
-1.700	0.847	0.032	0.000	0.005

Table 10. Mean weight (g) of sampled sea cucumbers in surveyed open fishing areas with significance of the test results of mean weight compared between years. * signifies a test with a significant difference (less than 0.05).

Open Fishing Area	Year; Mean Split Weight (g)	Year; Mean Split Weight (g)	Test Type	P-value
Area 7	1998; 353.4	2002; 286.6	Mann-Whitney U	<0.001*
Area 7	2002; 286.6	2006; 303.6	Mann-Whitney U	0.006*
Area 7	1998; 353.4	2006; 303.6	Mann-Whitney U	<0.001*
Fitz Hugh Sound	2002; 261.0	2006; 289.0	Mann-Whitney U	0.01*
Fitz Hugh Sound vs. Area 7	2002; 261.0	2002; 286.6	Mann-Whitney U	<0.01*
Fitz Hugh Sound vs. Area 7	2006; 289.0	2006; 303.6	Mann-Whitney U	<0.01*
Trutch	2001; 404.6	2005; 337.0	Mann-Whitney U	<0.01*
Gil/Gribbell	1999; 246.9	2003; 215.2	Mann-Whitney U	<0.01*
Gil/Gribbell	1999; 246.9	2007; 212.4	Mann-Whitney U	<0.01*
Gil/Gribbell	2003; 215.2	2007; 212.4	Mann-Whitney U	0.97
Area 12 Inlets	2000; 300.7	2004; 295.6	Independent t-test	0.56
Tofino	2001; 357.3	2005; 315.5	Mann-Whitney U	0.02*

Table 11. Significance of the test results, in the four Experimental Fishing Areas, of mean split drained weight of sea cucumbers compared between first year of biosampling and last year of biosampling. * signifies a test with a significant difference (less than 0.05), therefore means are different.

Open Fishing Area	Site	Year; Mean Split Weight (g)	Year; Mean Split Weight (g)	Test type	P-value
Laredo Inlet	0	1998; 242.9	2007; 311.2	Mann-Whitney U	<0.01*
Laredo Inlet	2	1999; 304.9	2007; 317.4	Mann-Whitney U	0.35
Laredo Inlet	4	1998; 245.3	2007; 291.6	Mann-Whitney U	<0.01*
Laredo Inlet	8	1998; 304.7	2007; 215.0	Mann-Whitney U	<0.01*
Laredo Inlet	16	1998; 253.5	2007; 258.0	Mann-Whitney U	0.67
Tolmie Channel	0	1998; 224.7	2007; 229.5	Anova; Bonferroni post-hoc	1.00
Tolmie Channel	2	1998; 277.5	2007; 275.6	Anova; Bonferroni post-hoc	1.00
Tolmie Channel	4	1998; 296.3	2007; 332.9	Anova; Bonferroni post-hoc	0.10
Tolmie Channel	8	1998; 321.7	2007; 329.9	Anova; Bonferroni post-hoc	1.00
Tolmie Channel	16	1998; 235.0	2007; 179.5	Anova; Bonferroni post-hoc	<0.01*
Jervis Inlet	0	1999; 254.4	2007; 187.0	Mann-Whitney U	<0.01*
Jervis Inlet	2	1999; 217.2	2007; 191.6	Mann-Whitney U	0.02*
Jervis Inlet	4	1999; 231.6	2007; 182.5	Mann-Whitney U	<0.01*
Jervis Inlet	8	1999; 273.4	2007; 218.8	Mann-Whitney U	<0.01*
Jervis Inlet	16	1999; 270.7	2007; 204.6	Mann-Whitney U	<0.01*
Zeballos	0	1999; 365.0	2007; 342.5	Mann-Whitney U	0.18
Zeballos	2	1999; 458.6	2007; 287.4	Mann-Whitney U	<0.01*
Zeballos	4	1999; 392.5	2007; 308.8	Mann-Whitney U	<0.01*
Zeballos	8	1999; 353.3	2007; 274.0	Mann-Whitney U	<0.001*
Zeballos	16	1999; 381.8	2007; 258.4	Mann-Whitney U	<0.001*

Table 12. Maximum sustainable harvest rates from the latent-productivity model, expressed as a fraction of virgin population per year, for each of the four experimental fishery areas. Results are given using both linear and spatial density estimates in the model simulations.

Location		Percentile on Maximum sustainable harvest rate (fraction of virgin biomass per year)					Estimated Virgin Biomass (tonnes)
		1%	5%	10%	25%	50%	
Jervis	Linear	0.076	0.080	0.082	0.087	0.092	95.325
	Spatial	0.067	0.079	0.088	0.101	0.114	115.094
Laredo	Linear	0.043	0.047	0.051	0.057	0.063	30.230
	Spatial	0.035	0.042	0.045	0.050	0.057	31.645
Tolmie	Linear	0.136	0.144	0.147	0.153	0.158	166.910
	Spatial	0.094	0.102	0.106	0.112	0.119	161.695
Zeballos	Linear	0.089	0.096	0.102	0.111	0.124	96.005
	Spatial	0.103	0.115	0.122	0.132	0.144	97.889

Table 13. Maximum recovery rate (kg per metre (linear) or per metre-squared (spatial) per year) from the latent-productivity model. Results are given using both linear and spatial density estimates in the model simulations.

Location		Percentile on Maximum Recovery Rate (Kilos per metre or per metre-squared per year)					Estimated Virgin Biomass Density (kg/metre or kg/metre-squared)
		1%	5%	10%	25%	50%	
Jervis	Linear	0.1239	0.1298	0.1331	0.1388	0.1457	1.589
	Spatial	0.0014	0.0017	0.0019	0.0022	0.0025	0.022
Laredo	Linear	0.0237	0.0261	0.0277	0.0306	0.0339	0.536
	Spatial	0.0005	0.0006	0.0006	0.0007	0.0008	0.014
Tolmie	Linear	0.4248	0.4469	0.4571	0.4739	0.4900	3.101
	Spatial	0.0074	0.0079	0.0083	0.0087	0.0093	0.078
Zeballos	Linear	0.1579	0.1707	0.1811	0.1971	0.2187	1.764
	Spatial	0.0040	0.0045	0.0048	0.0052	0.0056	0.039

Table 14. Posterior distributions for $x_{truncate}$ for each EFA. The estimated values are expressed as a fraction of virgin biomass. Lower values indicate that we have observed productivity at lower relative levels of abundance.

Location		Percentile on xtrunc				
		50%	75%	90%	95%	99%
Jervis	Linear	0.399	0.411	0.423	0.429	0.446
	Spatial	0.280	0.299	0.317	0.327	0.343
Laredo	Linear	0.449	0.474	0.495	0.508	0.535
	Spatial	0.462	0.486	0.509	0.522	0.546
Tolmie	Linear	0.365	0.381	0.397	0.405	0.425
	Spatial	0.401	0.418	0.436	0.447	0.463
Zeballos	Linear	0.460	0.487	0.515	0.527	0.553
	Spatial	0.368	0.395	0.420	0.434	0.459

Table 15. Effect of adding successive years of data to latent-productivity model simulations on the maximum sustainable harvest rates

Location		Percentile on Maximum sustainable harvest rate (fraction of virgin population per year)					DIC	Effective Number of Parameters	Estimated Virgin Biomass Density (kg/metre or kg/metre-squared)	Standard Deviations (geometric)		
		1%	5%	10%	25%	50%				year	site	transect
Jervis to 2005	Linear	0.069	0.076	0.080	0.088	0.096	5656	104.6	1.551	0.211	0.401	1.205
	Spatial	0.046	0.052	0.057	0.064	0.075	**5257**	104.5	0.022	0.506	0.194	1.300
Jervis with 2007	Linear	0.076	0.080	0.082	0.087	0.092	6964	102.5	1.589	0.207	0.410	1.181
	Spatial	0.067	0.079	0.088	0.101	0.114	**6502**	108.7	0.022	0.512	0.167	1.292
Laredo to 2003	Linear	0.059	0.076	0.088	0.106	0.126	2332	77.4	0.531	0.124	0.456	0.847
	Spatial	0.051	0.069	0.083	0.105	0.128	**2260**	78.3	0.013	0.165	0.356	0.904
Laredo with 2005	Linear	0.034	0.044	0.049	0.059	0.073	2597	77.8	0.538	0.128	0.484	0.843
	Spatial	0.020	0.026	0.031	0.040	0.051	2511	78.8	0.014	0.169	0.385	0.901
Laredo with 2007	Linear	0.043	0.047	0.051	0.057	0.063	3051	78.2	0.536	0.135	0.544	0.863
	Spatial	0.035	0.042	0.045	0.050	0.057	**2944**	78.4	0.014	0.177	0.430	0.918
Tolmie to 2003	Linear	0.198	0.207	0.211	0.218	0.227	4755	86.8	3.069	0.216	0.441	0.615
	Spatial	0.175	0.188	0.193	0.203	0.215	**4622**	86.2	0.077	0.203	0.205	0.545
Tolmie with 2005	Linear	0.138	0.146	0.151	0.158	0.165	6067	88.4	3.088	0.183	0.374	0.571
	Spatial	0.086	0.099	0.105	0.113	0.124	**5858**	88.1	0.077	0.176	0.164	0.496
Tolmie with 2007	Linear	0.136	0.144	0.147	0.153	0.158	6742	89.0	3.101	0.260	0.354	0.551
	Spatial	0.094	0.102	0.106	0.112	0.119	**6528**	88.8	0.078	0.243	0.158	0.482
Zeballos to 2005	Linear	0.071	0.078	0.082	0.091	0.102	2505	72.0	1.686	0.155	0.262	0.262
	Spatial	0.069	0.076	0.083	0.099	0.117	**2374**	74.5	0.037	0.100	0.266	0.943
Zeballos with 2007	Linear	0.089	0.096	0.102	0.111	0.124	3430	75.1	1.764	0.156	0.184	0.838
	Spatial	0.103	0.115	0.122	0.132	0.144	**3305**	76.1	0.039	0.118	0.211	0.822

Table 16. Summary of sea cucumber linear density, by ShoreZone exposure class.

Trutch 2001		**ShoreZone Exposure Class**					
		Very Exposed	**Exposed**	**Semi-Exposed**	**Semi-Protected**	**Protected**	**Very Protected**
No. Transects		*	18	95	25	13	2
Percent of Total		0.0%	11.8%	62.1%	16.3%	13%	1.3%
Cucumbers per meter shoreline	**Maximum**		11	53.8	25.5	20.5	3.25
	Mean		2.35	7.5	6.3	7.4	2.5
	Minimum		0	0	0	0	1.75
	Mode		0	0	6.3	N/A	N/A

* Many transects were not completed that would likely have been Very Exposed or Exposed

Gil/Gribbell 1999		**ShoreZone Exposure Class**					
		Very Exposed	**Exposed**	**Semi-Exposed**	**Semi-Protected**	**Protected**	**Very Protected**
No. Transects				15	187	34	
Percent of Total				6.4%	79.2%	14.4%	
Cucumbers per meter shoreline	**Maximum**			35.5	143	55.5	
	Mean			17.9	21	13.6	
	Minimum			3.3	0	0	
	Mode			14.75	6.75	9.25	

Tofino 2001		**ShoreZone Exposure Class**					
		Very Exposed	**Exposed**	**Semi-Exposed**	**Semi-Protected**	**Protected**	**Very Protected**
No. Transects			4	12	38	101	
Percent of Total			2.6%	7.7%	24.5%	65.2%	
Cucumbers per meter shoreline	**Maximum**		4.5	31.5	28.3	132.5	
	Mean		1.4	6.6	4.3	6.9	
	Minimum		0	0	0	0	
	Mode		0	0	0	0	

Area 7 1998		**ShoreZone Exposure Class**					
		Very Exposed	**Exposed**	**Semi Exposed**	**Semi Protected**	**Protected**	**Very Protected**
No. Transects					120	74	3
Percent of Total					60.9%	37.6%	1.5%
Cucumbers per meter shoreline	**Maximum**				66.75	93	32.25
	Mean				15.16	16.8	17.25
	Minimum				05.25	0	0
	Mode					0	N/A

Table 17. ShoreZone exposure classes where highest linear density of sea cucumbers were found (indicated by red highlights).

Maximum Fetch (Km)	Modified Effective Fetch (Km)				
	< 1	1 – 10	10 - 50	50 - 500	> 500
< 1	Very Protected				
1 – 10	Protected	Protected			
10 – 50		Semi-Protected	Semi-Protected		
50 – 500			Semi-Exposed	Semi-Exposed	
500 – 1,000			Semi-Exposed	Exposed	Exposed
> 1,000				Very Exposed	Very Exposed

Table 18. Dissolved fishing effort in relation to ShoreZone exposure class. Blue highlights indicate exposure classes where fishing efforts was seen to be concentrated, based on a preliminary visual analysis.

Maximum Fetch (Km)	Modified Effective Fetch (Km)				
	< 1	1 – 10	10 - 50	50 - 500	> 500
< 1	Very Protected				
1 – 10	**Protected**	**Protected**			
10 – 50		**Semi-Protected**	**Semi-Protected**		
50 – 500			**Semi-**Exposed	**Semi-**Exposed	
500 – 1,000			Semi-Exposed	Exposed	Exposed
> 1,000				Very Exposed	Very Exposed

Table 19. Shoreline length in each ShoreZone exposure class for PFMA 6. (Lengths are rounded to the nearest meter, totals are in kilometres).

Management Subarea	Very Exposed (m)	Exposed (m)	Semi-Exposed (m)	Semi-Protected (m)	Protected (m)	Very Protected (m)	Unclassed (m)
6-1				140,064	301,278		13,264
6-2				102,758	59,062		184
6-3				140,245	22,136		
6-4				2,061	321,892		
6-5			27,824	153,999	59,914		21,636
6-6				82,140	18,146		
6-7				24,311	8,201		
6-8			1,919	1,738	40,571		
6-9		37,305	194,950	104,471	128,185	6,511	879
6-10		23,901	99,144	61,345	73,502	2,406	97
6-11			10,159	501			
6-12			3,421	38,945	88,446	11,097	
6-13	2,208	25,132	182,145	118,207	97,917	3,482	1,527
6-14			35,810	12,723	33,073		
6-15			21,309	7,655	10,842		
6-16		27,093	59,768	39,549	32,525	4,761	
6-17		19,232	29,673	14,963	3,075		694
6-18			8,168	26,889	18,694	5,003	
6-19			30,804	56,406	173,791	2,135	
6-20			16	163,385	32,183		
6-21				3,291	14,596		1326
6-22				1,624	16,117		
6-23				9,115	20,983		1132
6-24				2,973	16,173		930
6-25			690	21,643	63,266		
6-26			58	16,360	2,972		
6-27			470	7,887	1,907		
6-28				23,256	1,355		
Total (km)	2.2	132.66	576.64	1,377.23	1,660.80	35.39	41.67

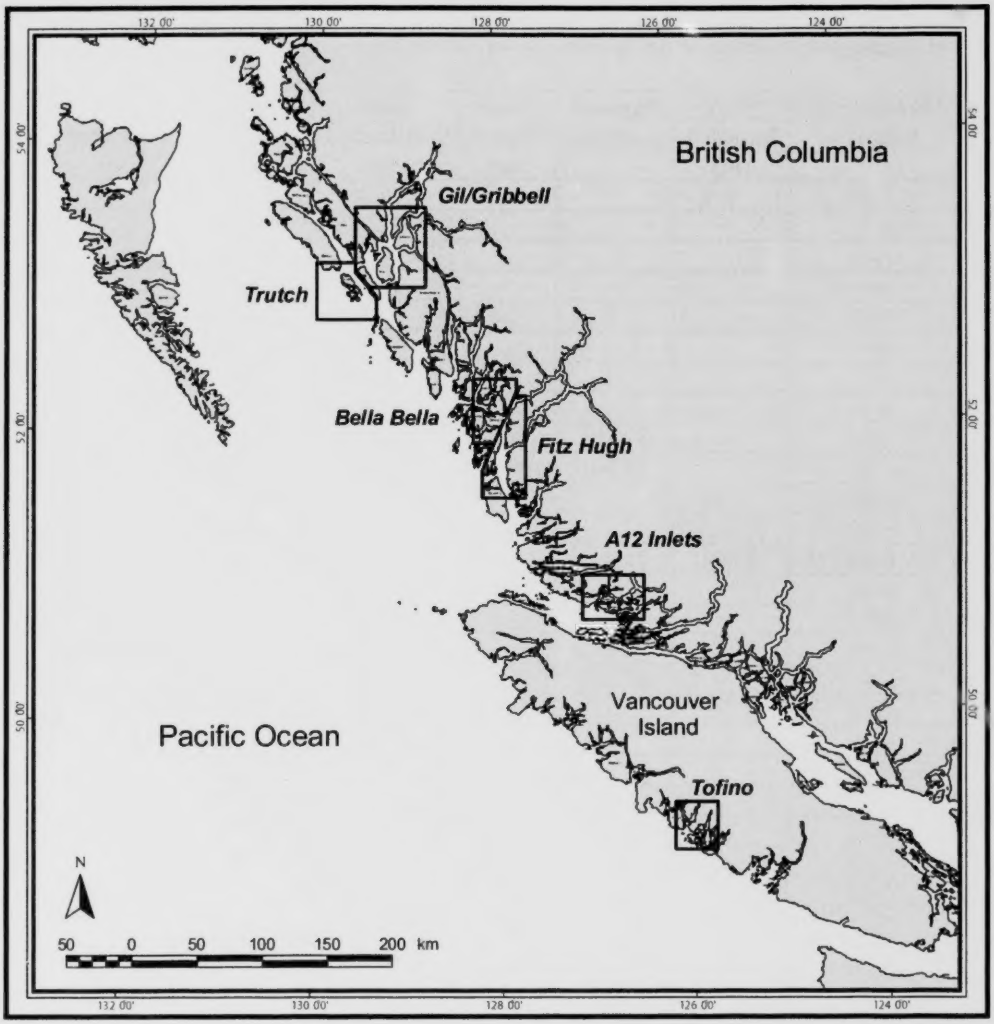


Figure 1. Map showing locations of open surveys in British Columbia.

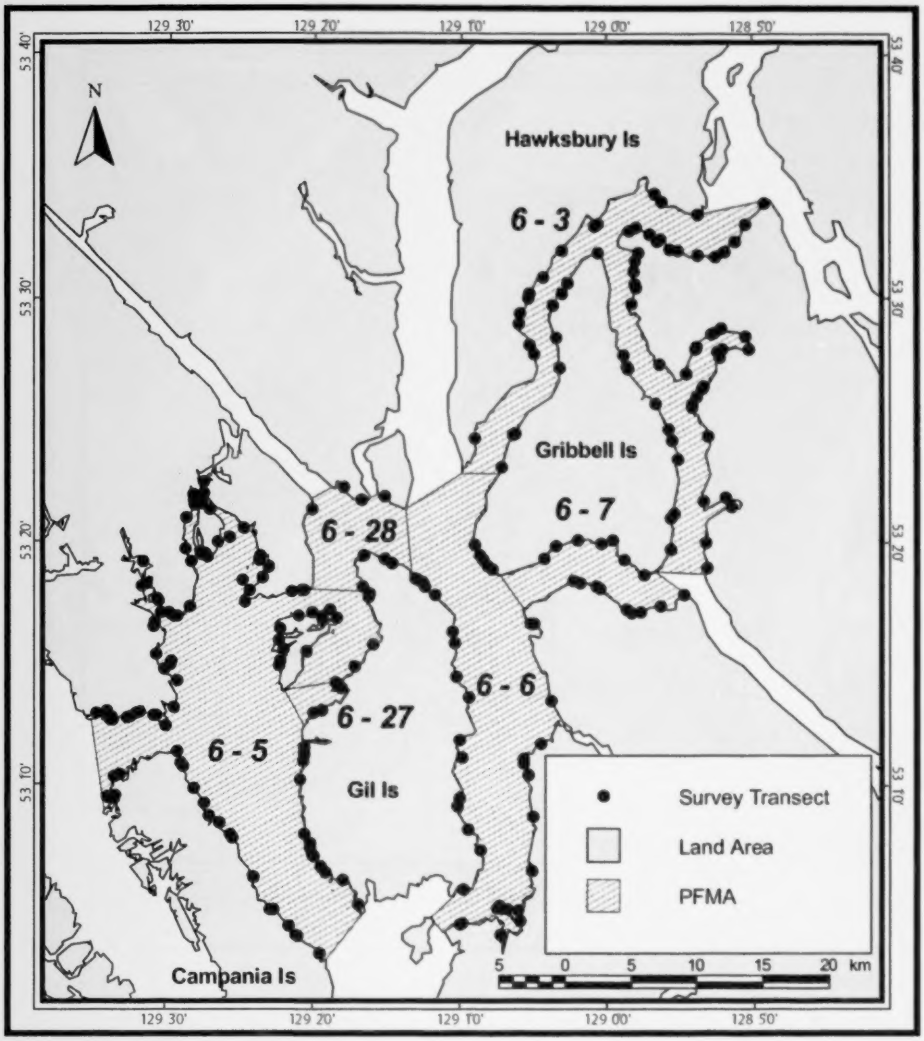


Figure 2. Map showing transects locations in the Gil Gribbell survey.

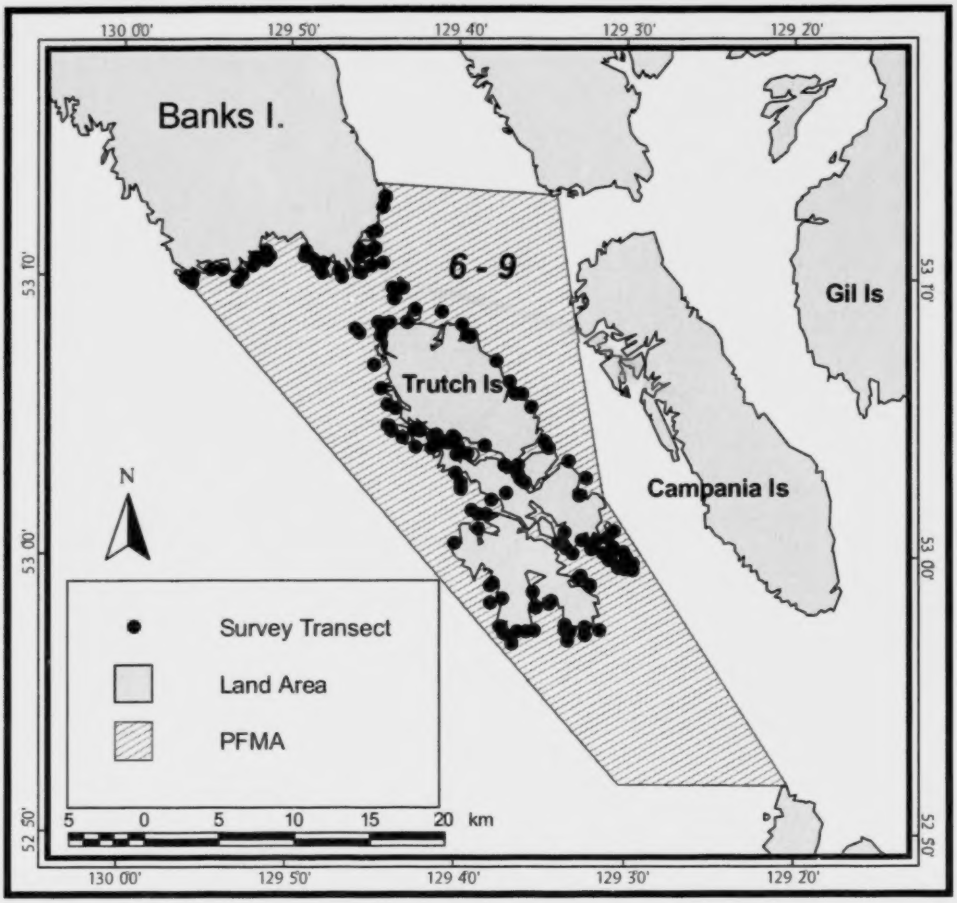


Figure 3. Map showing transects locations in the Trutch survey.

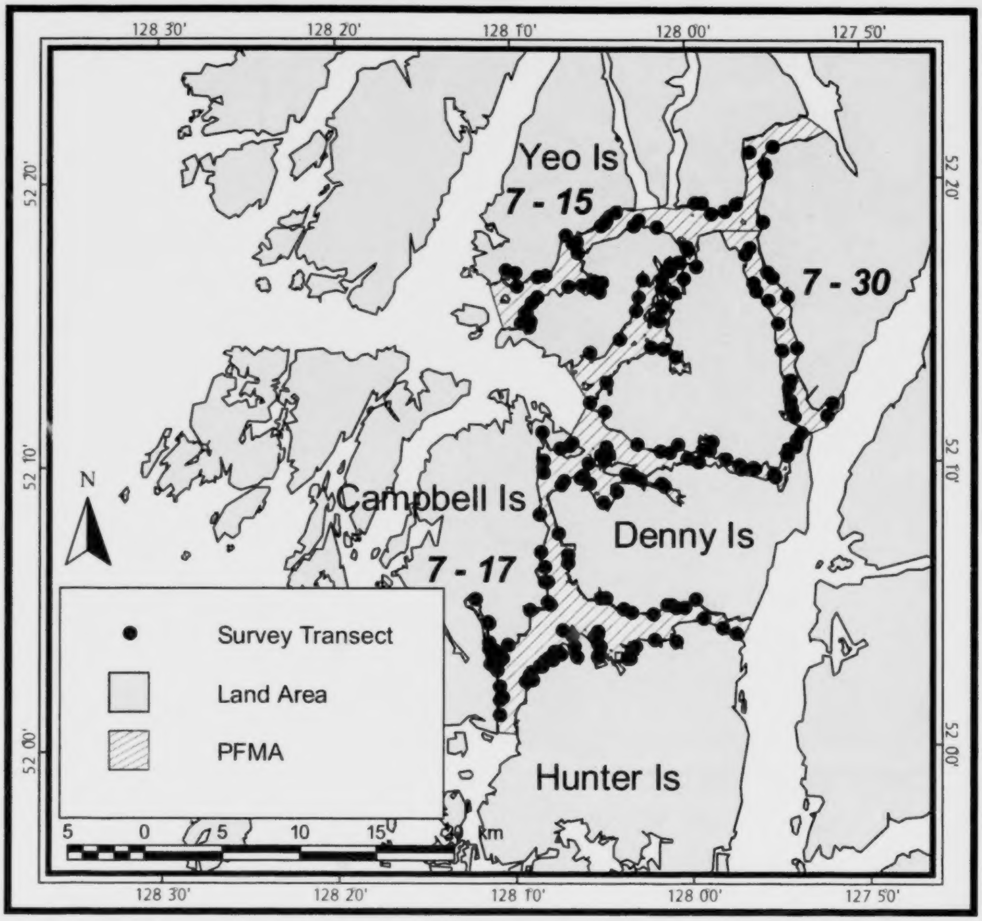


Figure 4. Map showing transects locations in the Area 7 survey.

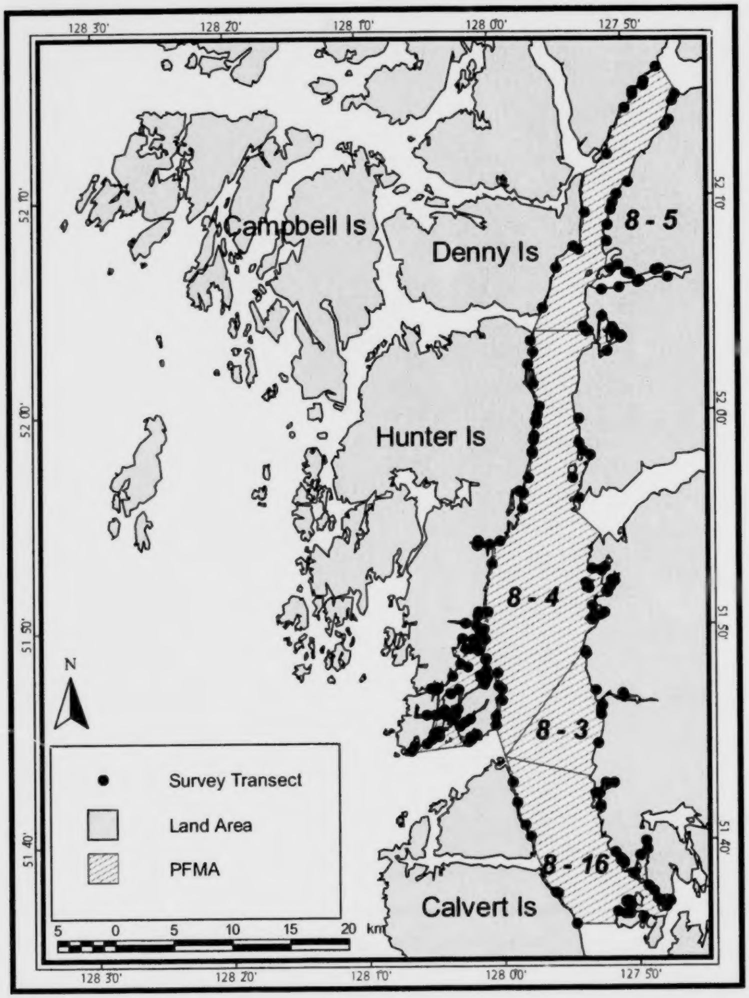


Figure 5. Map showing transects locations in the Fitz Hugh Sound survey.

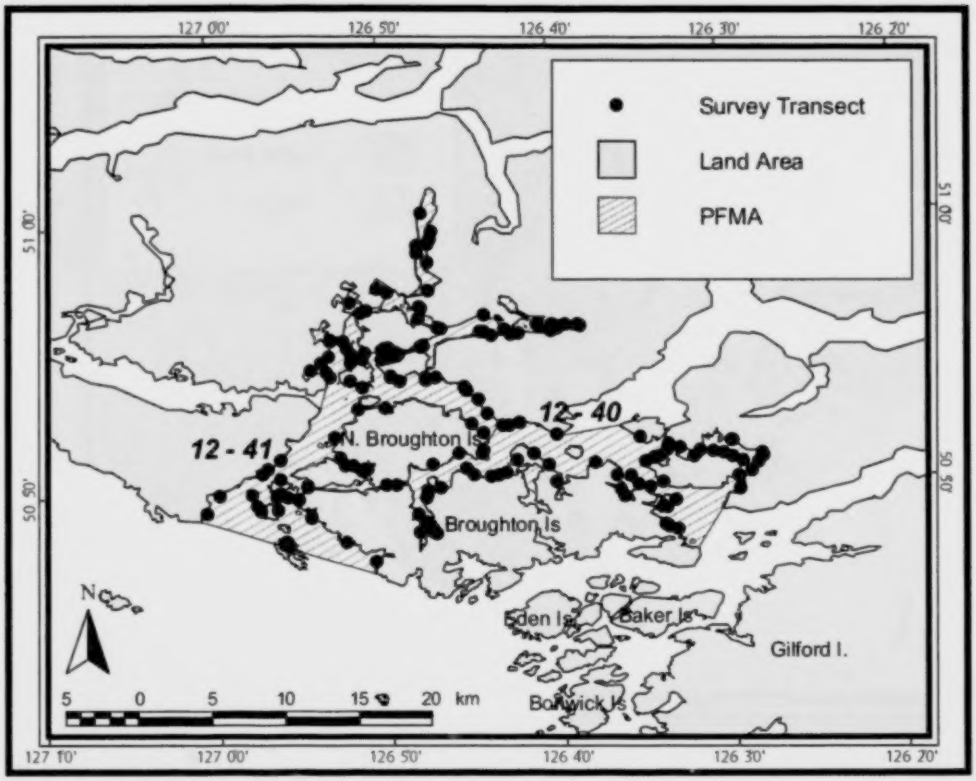


Figure 6. Map showing transects locations in the Area 12 survey.

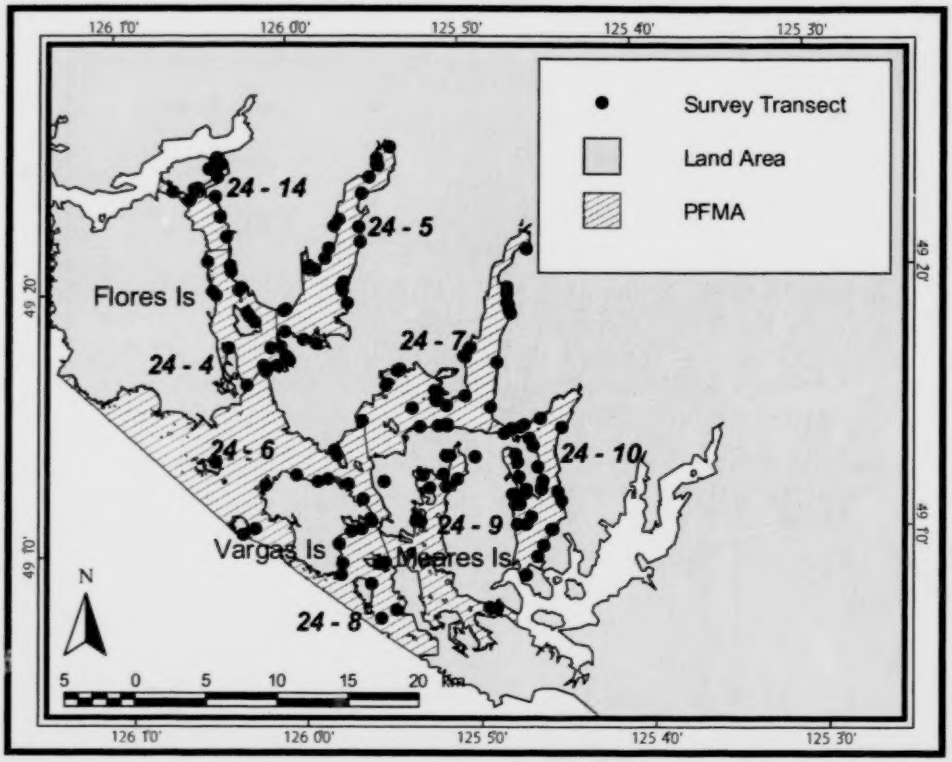


Figure 7. Map showing transects locations in the Area 24 survey.

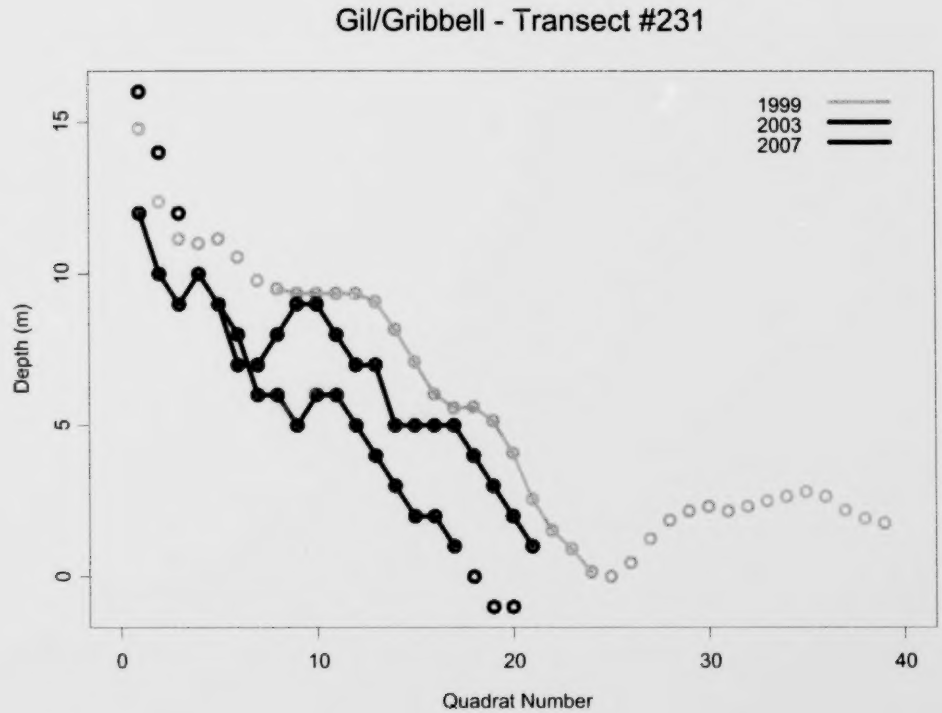


Figure 8. Depth profile of transect #231 in the Gil/Gribbell survey area that was surveyed in 1999, 2003 and 2007. Joined circles represent the common depth range.

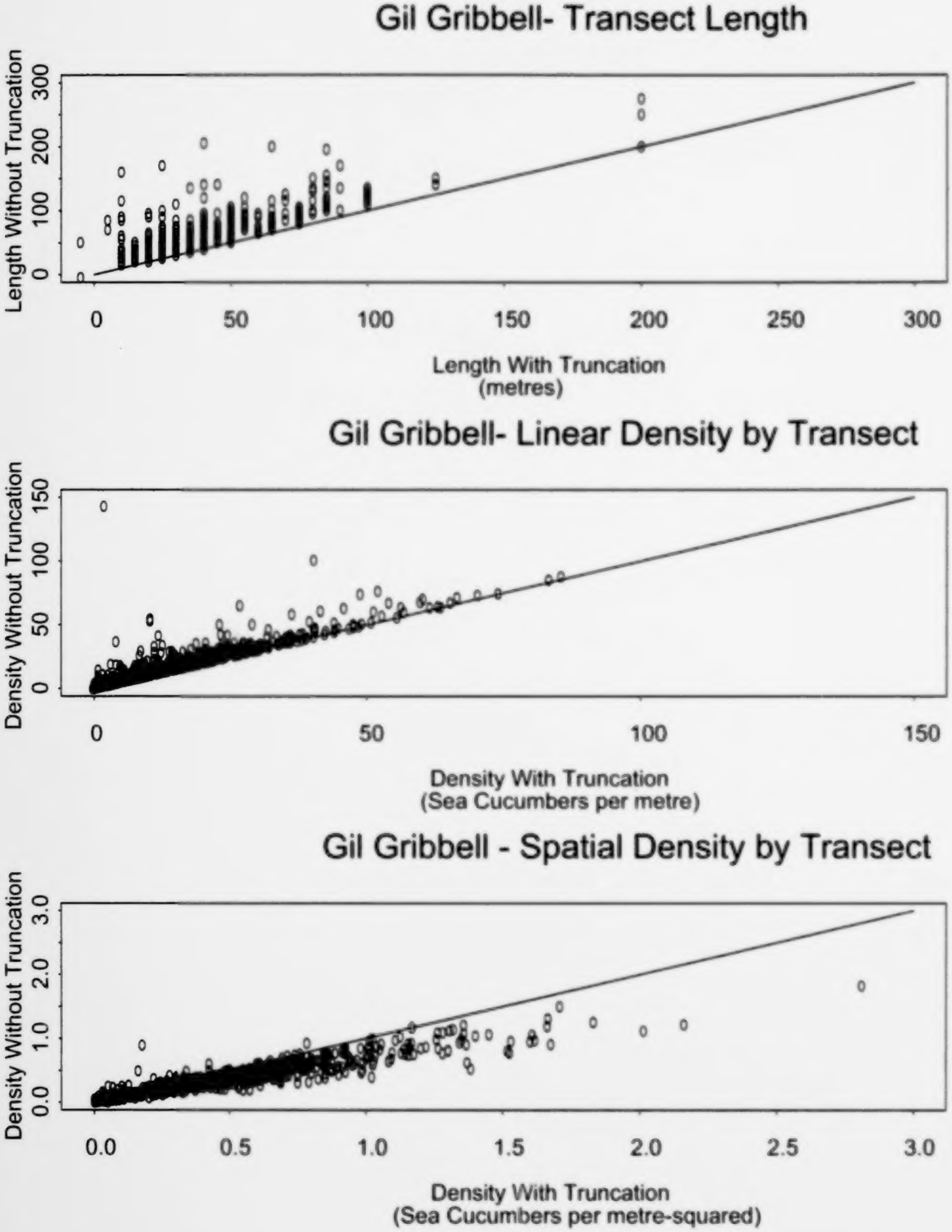


Figure 9. The effect of data-truncation on transect length and on linear and spatial density estimates for transects in Gil/Gribbell. Only transects that were surveyed all three years were used, and each transect appears three times.

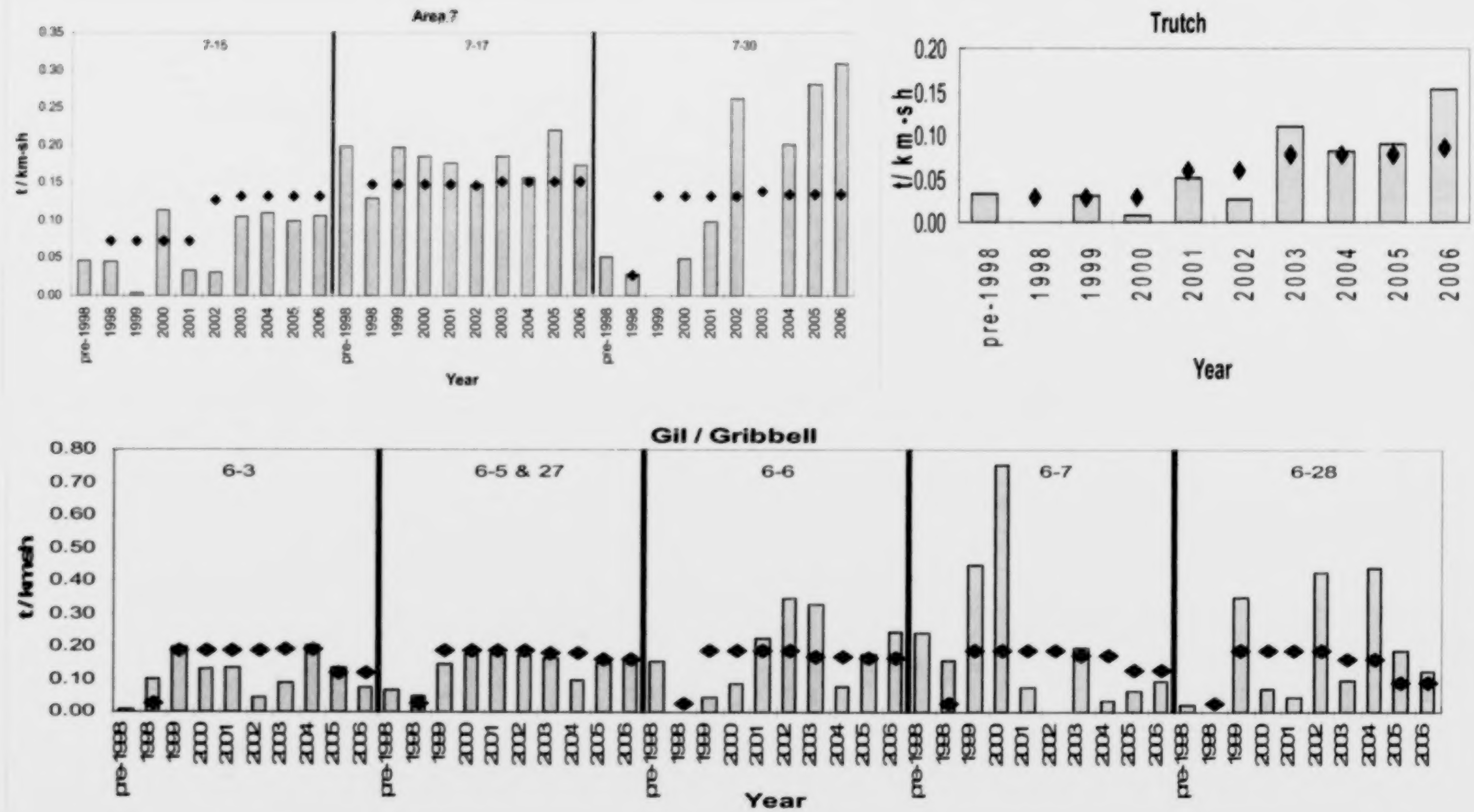
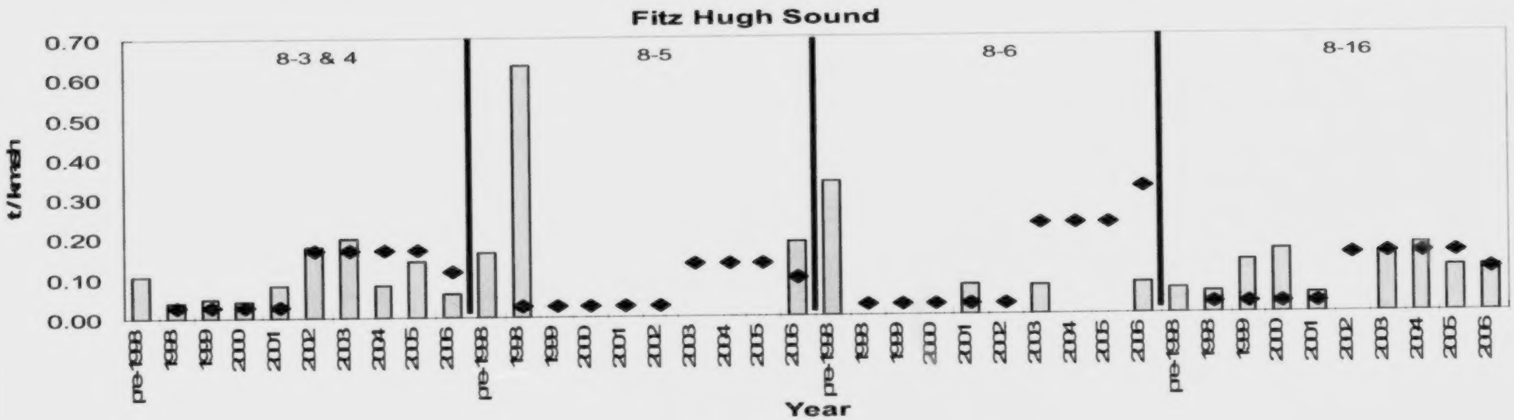
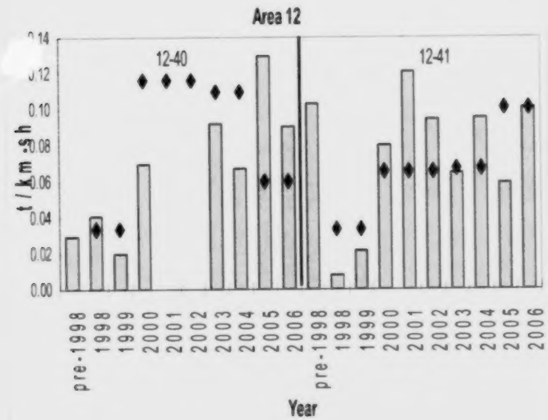


Figure 10. Landings (bars) and quotas (dots) in tonnes (split weight) per kilometre of shoreline by Subarea and year for each of the open survey areas. Pre-1998 landings are pooled and averaged over the period 1985 to 1997.





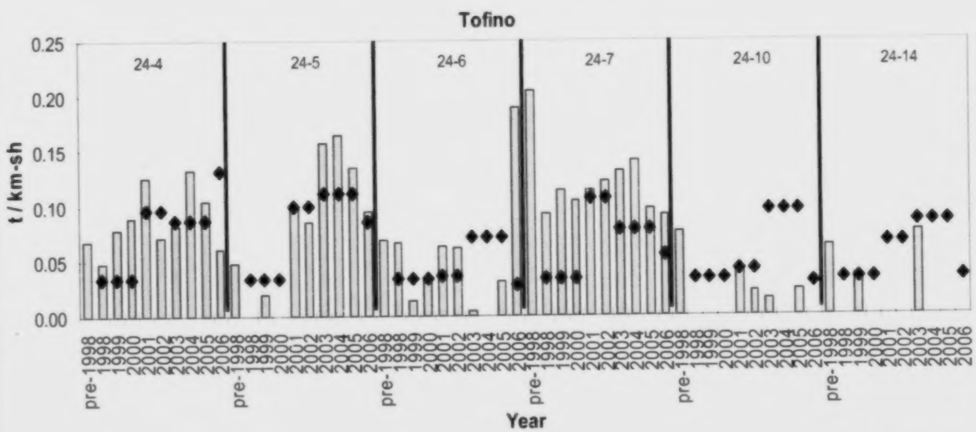


Figure 10, cont'd.

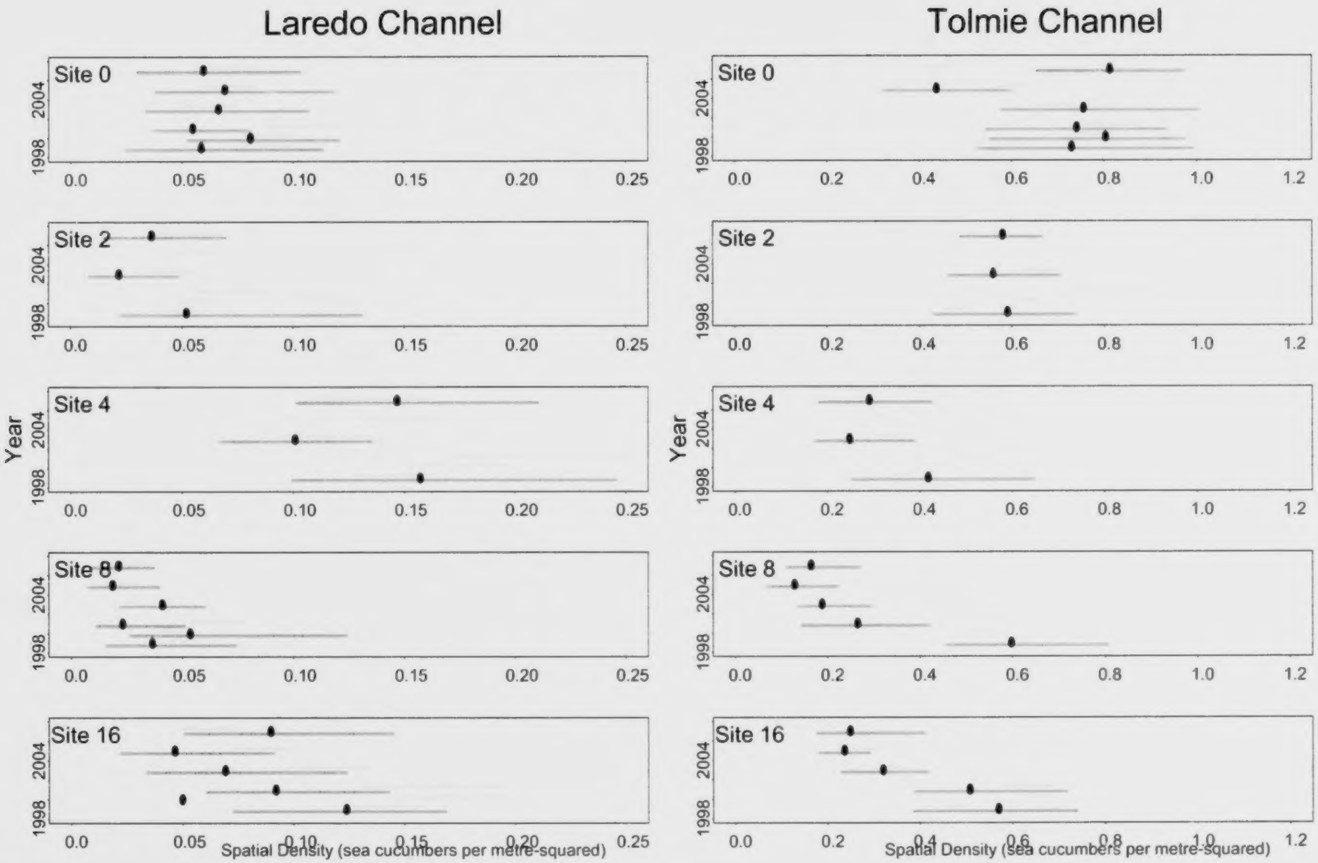


Figure 11. Spatial density of sea cucumbers, by EFA, harvest Site and survey year, from Laredo, Tolmie, Jervis and Zeballos. Circles and orange bars are the estimated mean and associated 95% confidence intervals (bootstrapping) as calculated from individual combinations of site and year. The pink bars are 95% confidence intervals on mean spatial density, as calculated from the latent-productivity model.

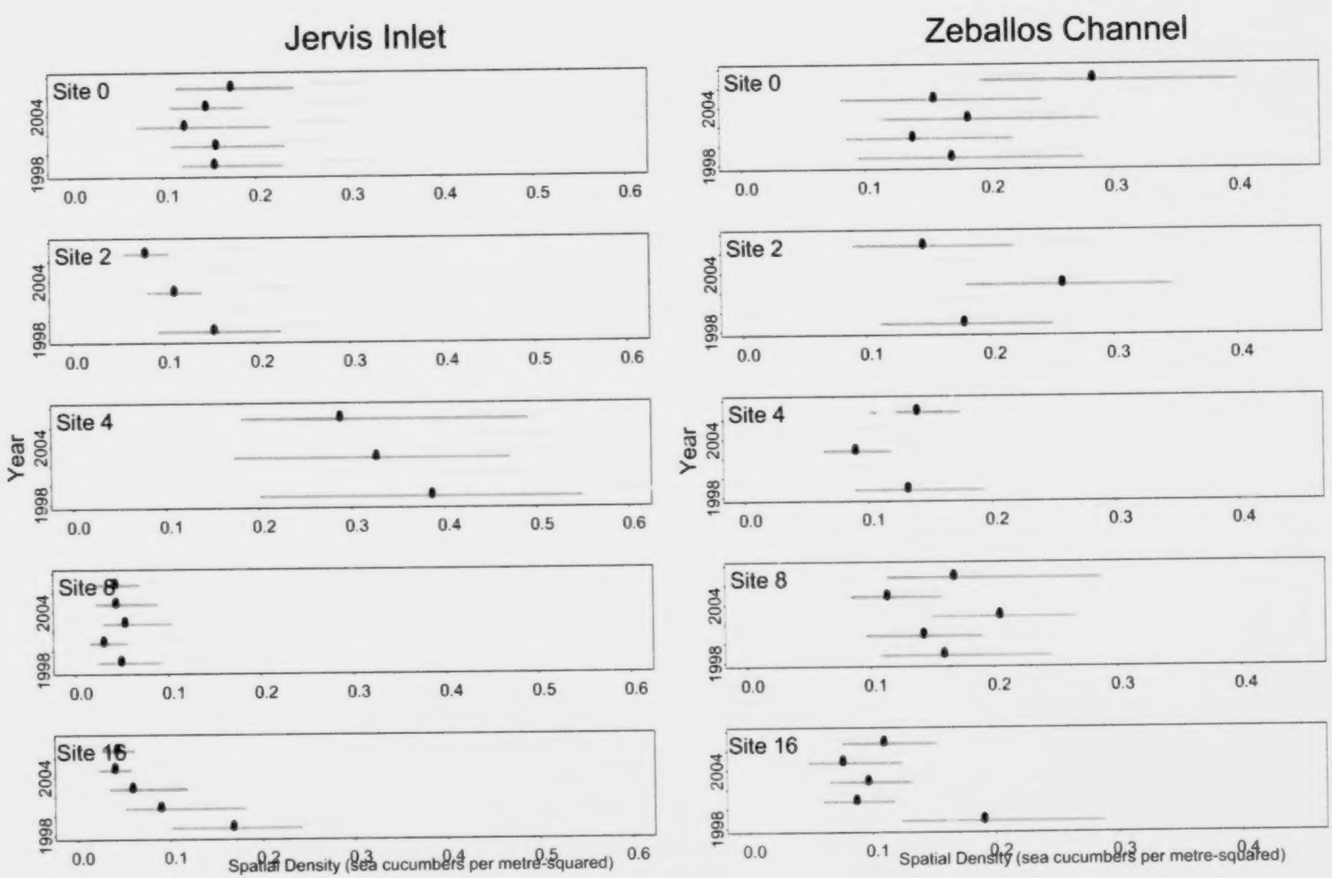


Figure 11, cont'd.

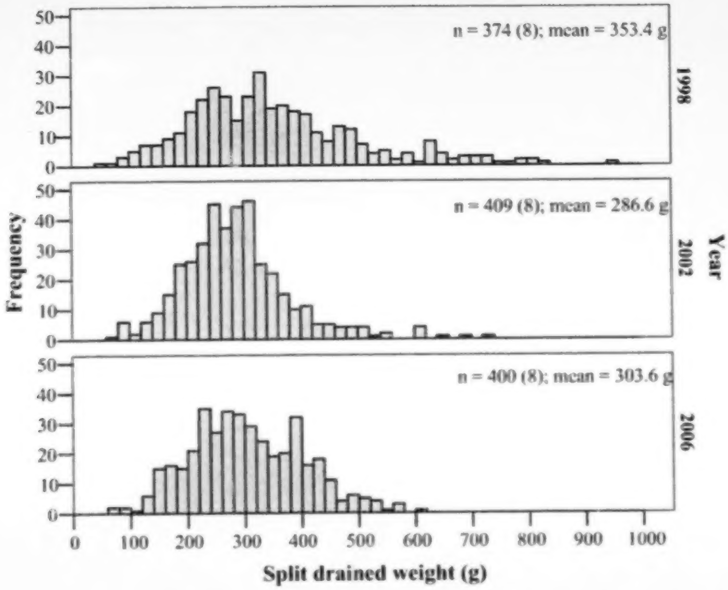


Figure 12a. Frequency distribution of sea cucumber split weight from samples collected in Area 7 in 1998, 2002, 2006. Number in brackets is the number of transects sampled.

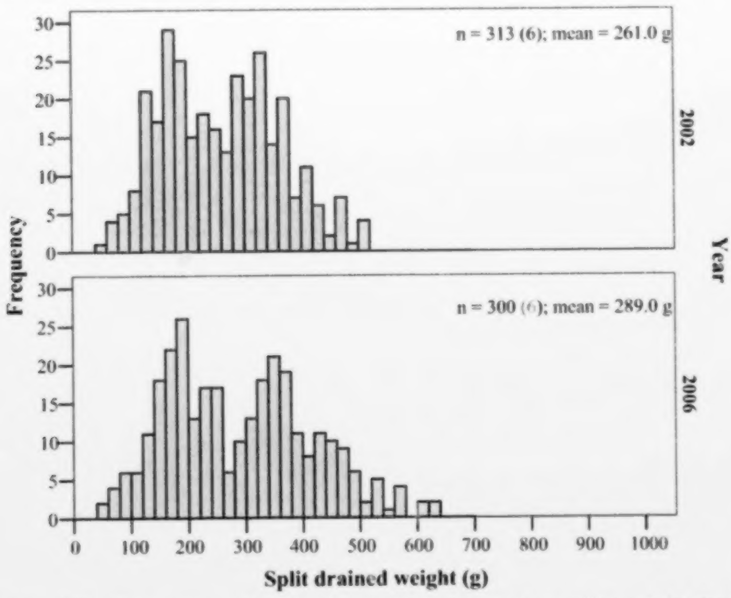


Figure 12b. Frequency distribution of sea cucumber split weight from samples collected in Fitz Hugh Sound in 2002 and 2006. Number in brackets is the number of transects sampled.

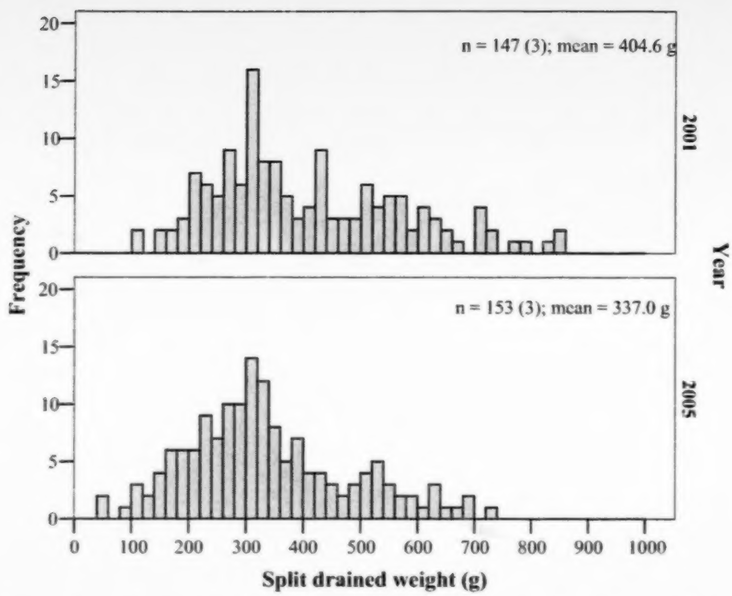


Figure 12c. Frequency distribution of sea cucumber split weight from samples collected in Trutch in 2001 and 2005. Number in brackets is the number of transects sampled.

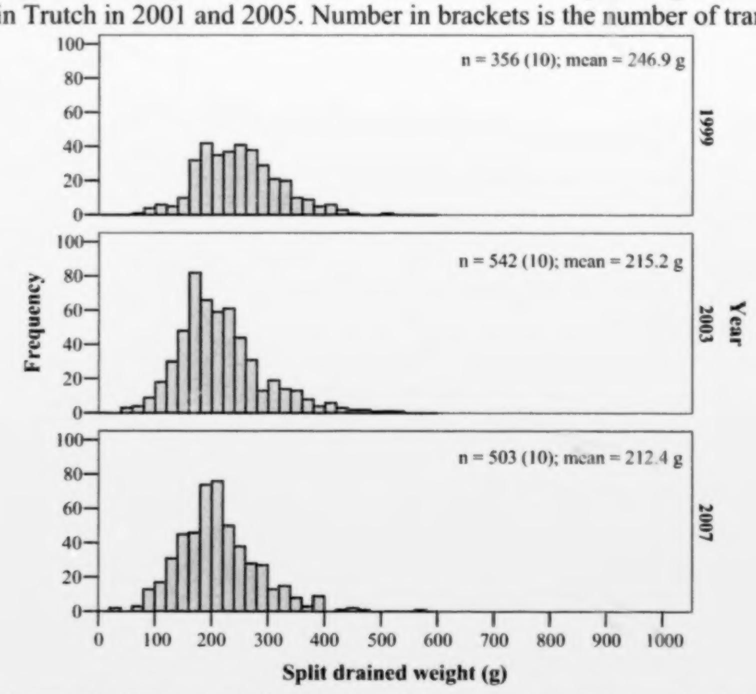


Figure 12d. Frequency distribution of sea cucumber split weight from samples collected in Gil/Gribbell in 1999, 2003 and 2007. Number in brackets is the number of transects sampled.

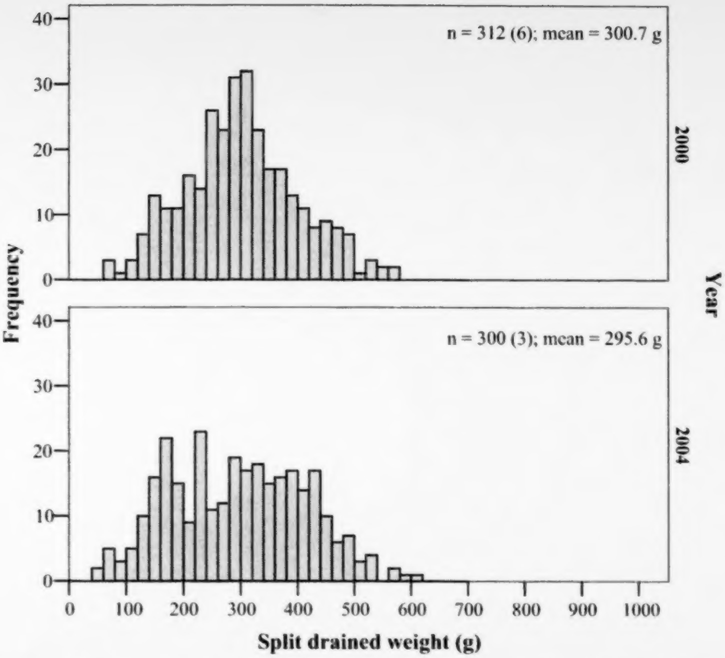


Figure 12e. Frequency distribution of sea cucumber split weight from samples collected in Area 12 Inlets in 2000 and 2004. Number in brackets is the number of transects sampled.

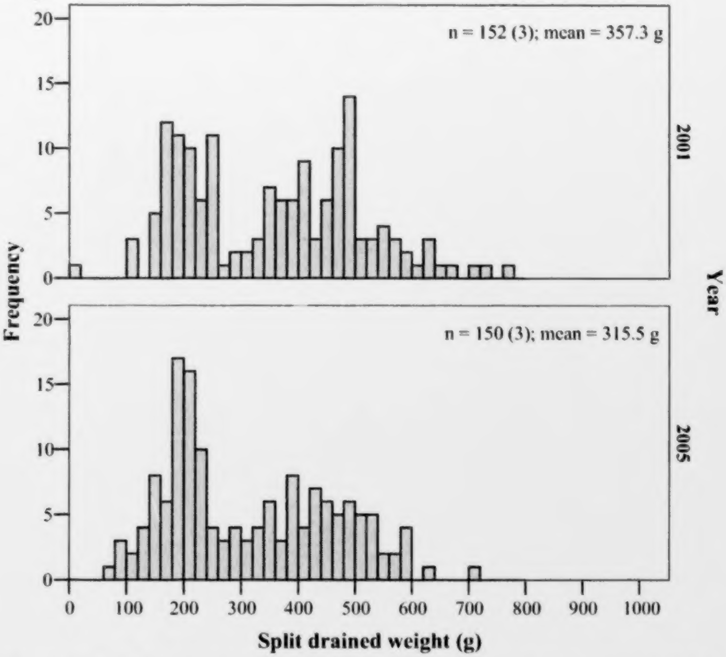


Figure 12f. Frequency distribution of sea cucumber split weight from samples collected in Tofino in 2001 and 2005. Number in brackets is the number of transects sampled.

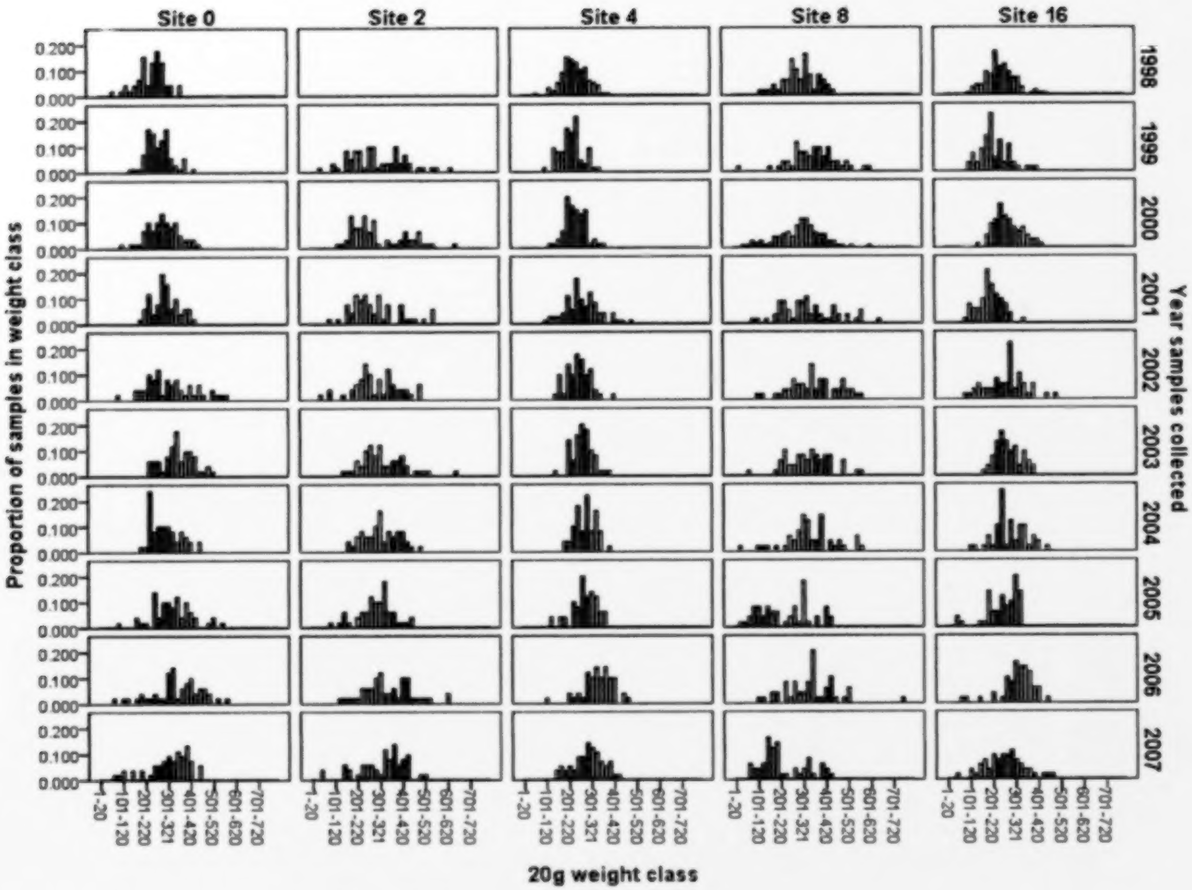


Figure 13a. Distribution histogram of split weights of 2,773 sea cucumbers in 85 biosamples taken from 5 sites in the Laredo Inlet EFA from 1998–2007.

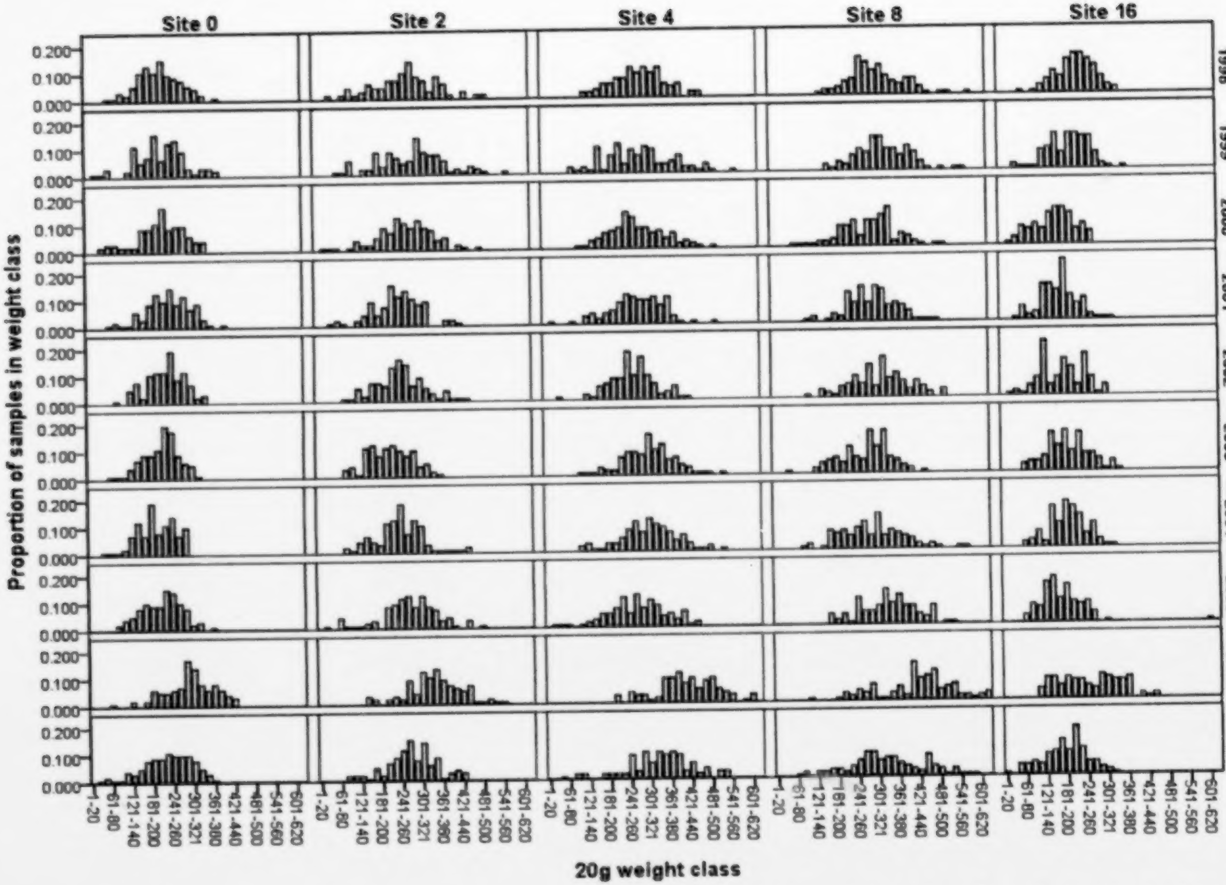


Figure 13b. Distribution histogram of split weights of 4,993 sea cucumbers in 90 biosamples taken from 5 sites in the Tolmie Channel EFA from 1998–2007.

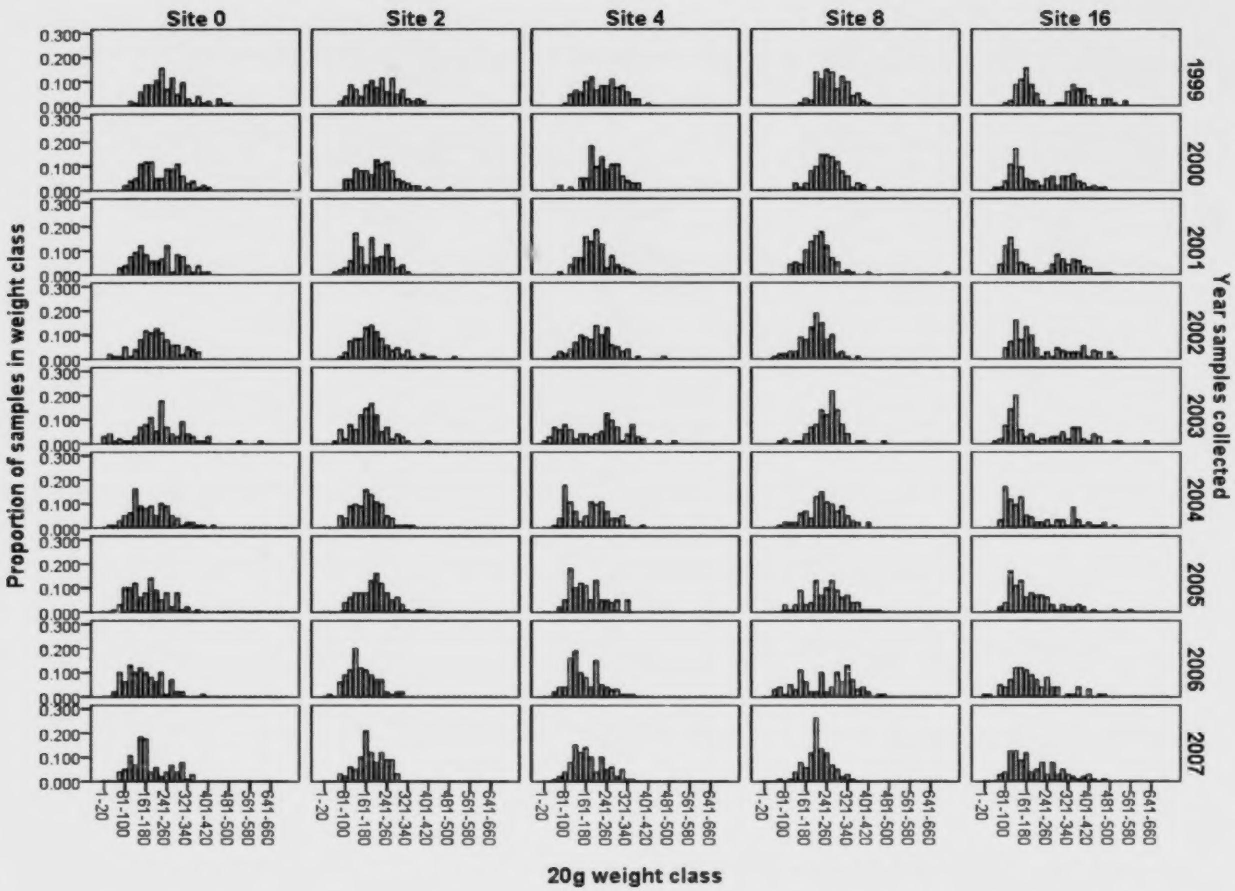


Figure 13c. Distribution histogram of split weights of 4,664 sea cucumbers in 89 biosamples taken from 5 sites in the Jervis Inlet EFA from 1999–2007.

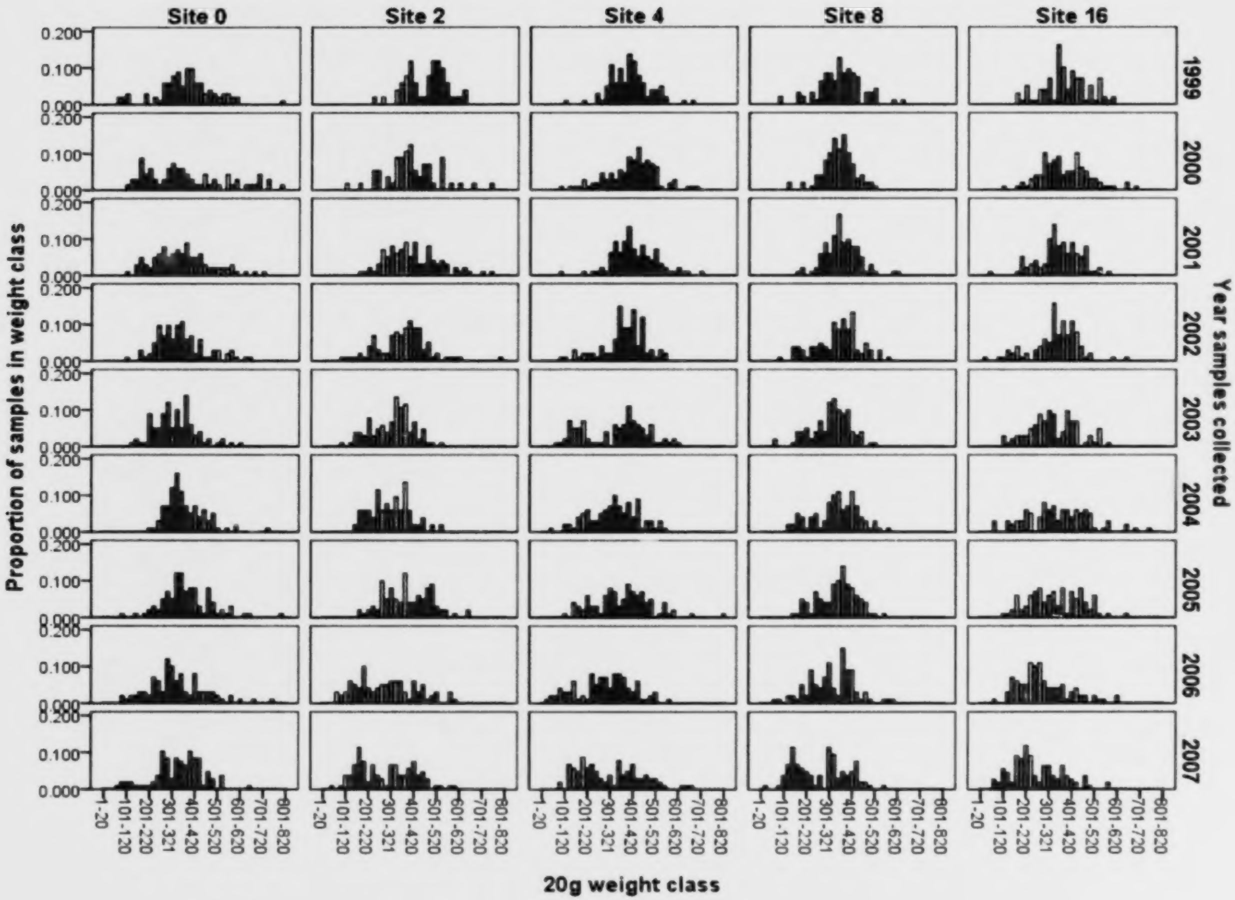


Figure 13d. Distribution histogram of split weights of 4,391 sea cucumbers in 89 biosamples taken from 5 sites in the Zeballos EFA from 1999–2007.

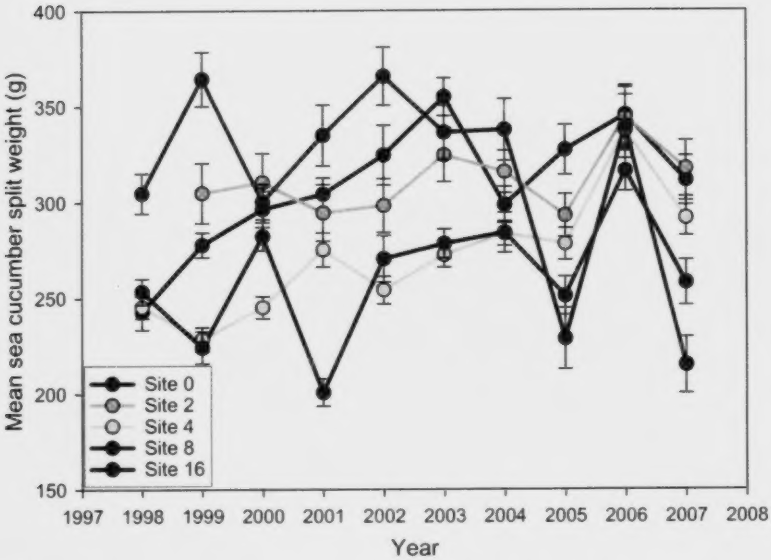


Figure 14a. Mean split weight and standard error of sea cucumbers collected in Laredo Inlet.

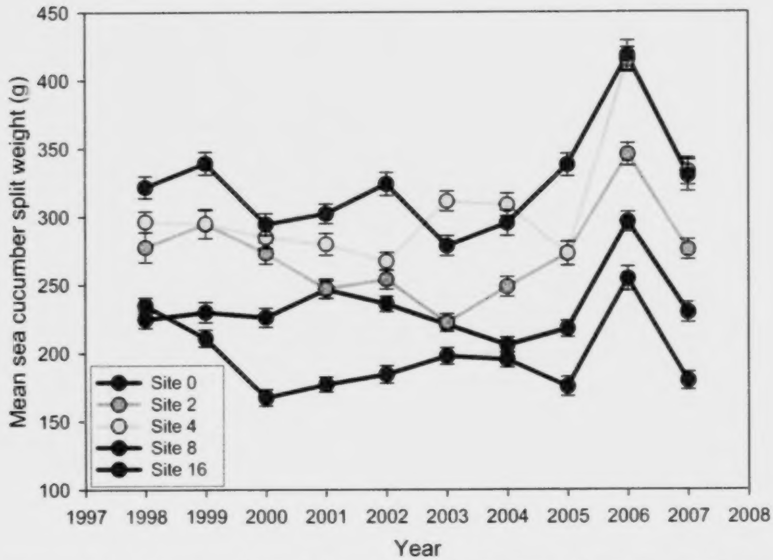


Figure 14b. Mean split weight and standard error of sea cucumbers collected in Tolmie Channel.

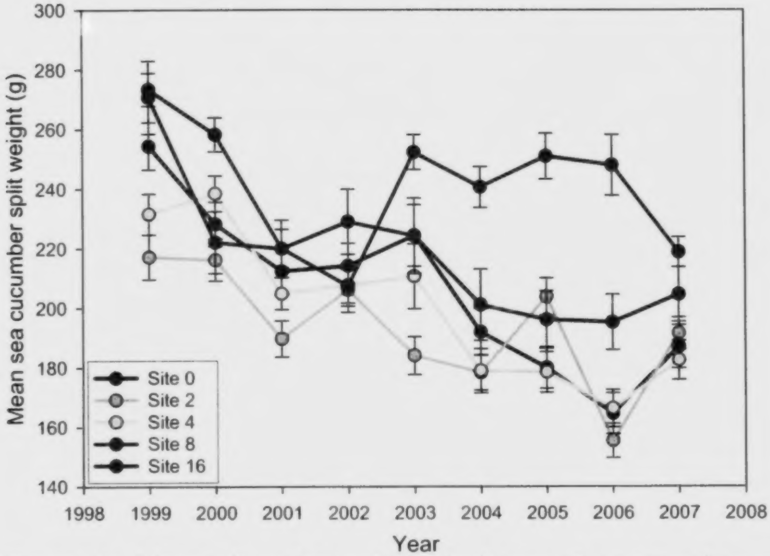


Figure 14c. Mean split weight and standard error of sea cucumbers collected in Jervis Inlet.

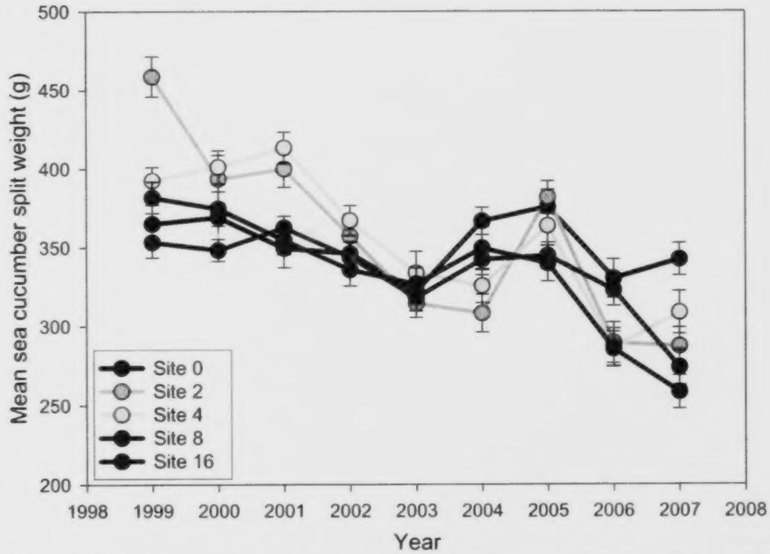


Figure 14d. Mean split weight and standard error of sea cucumbers collected in Zeballos.

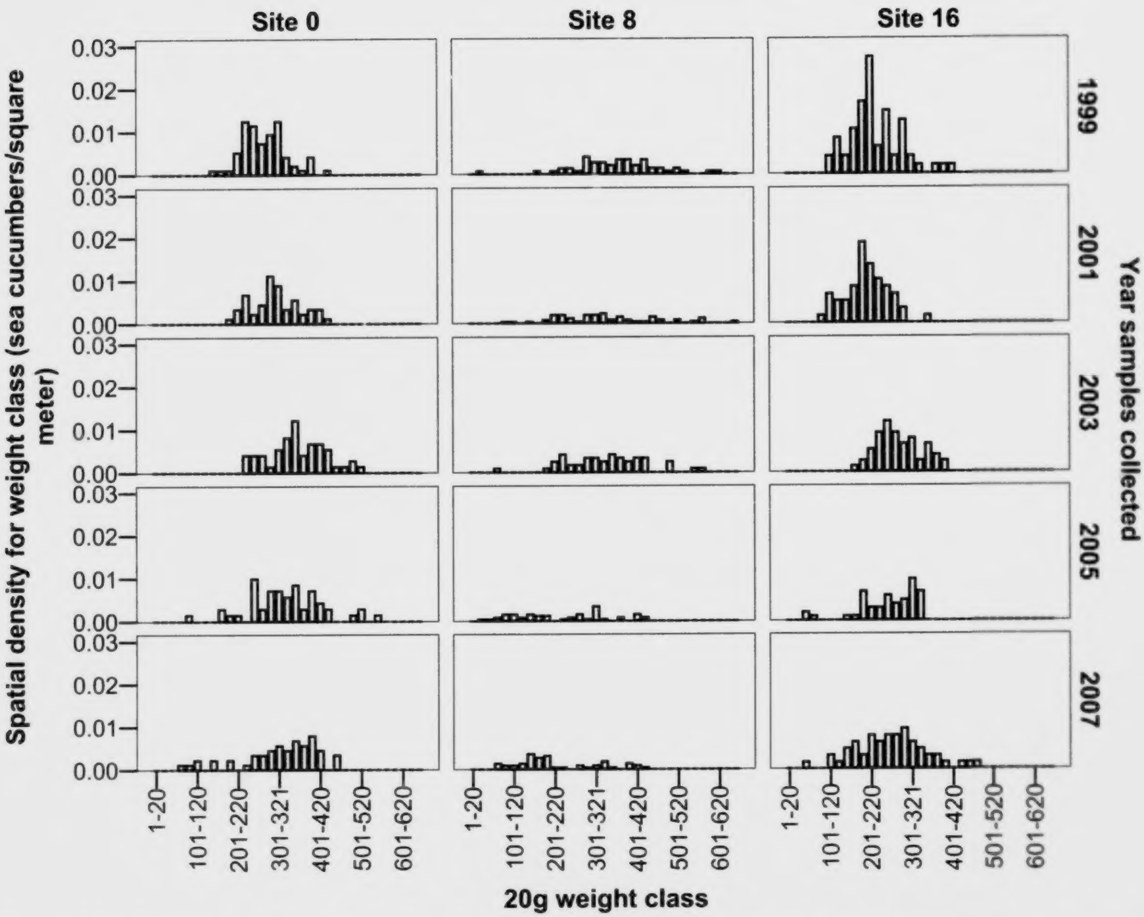


Figure 15a. Spatial density of 20 g weight classes of biosamples collected during surveys in the Laredo Inlet EFA.

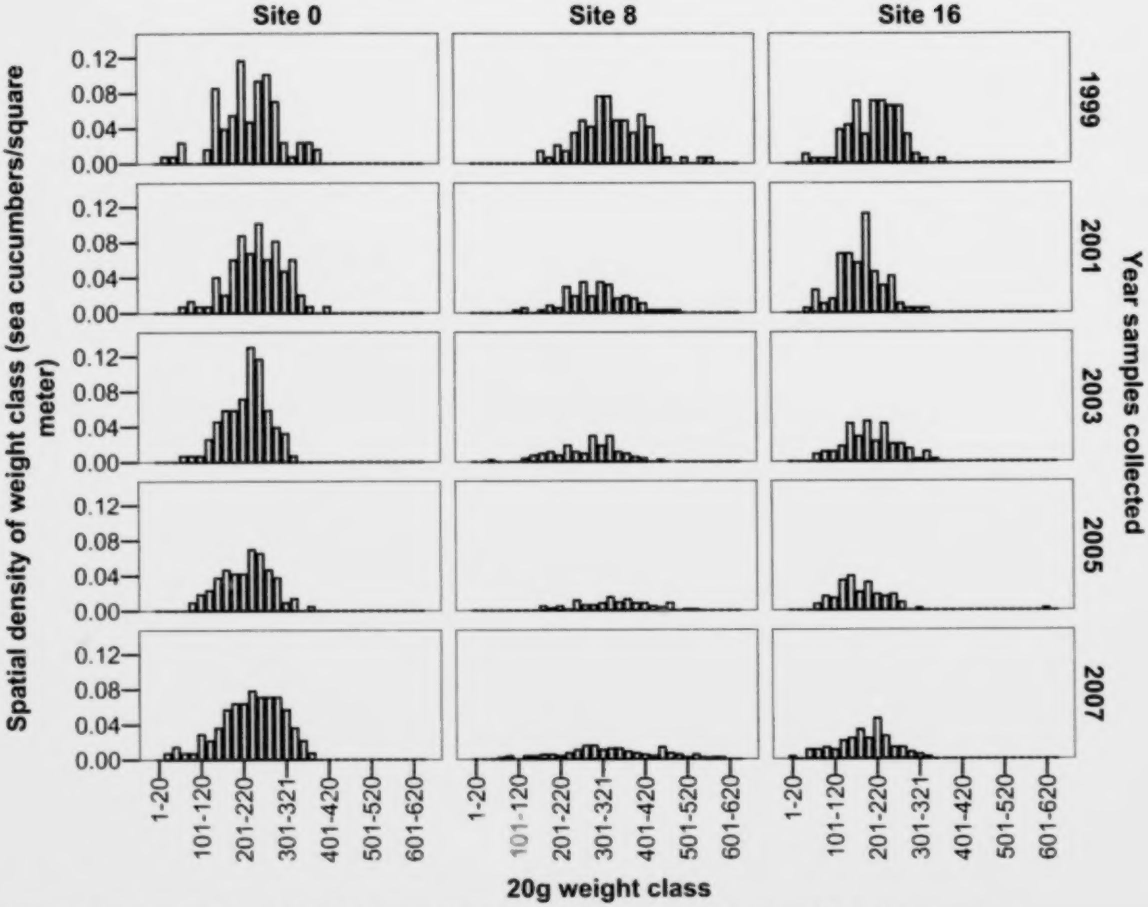


Figure 15b. Spatial density of 20 g weight classes of biosamples collected during surveys in the Tolmie Channel EFA.

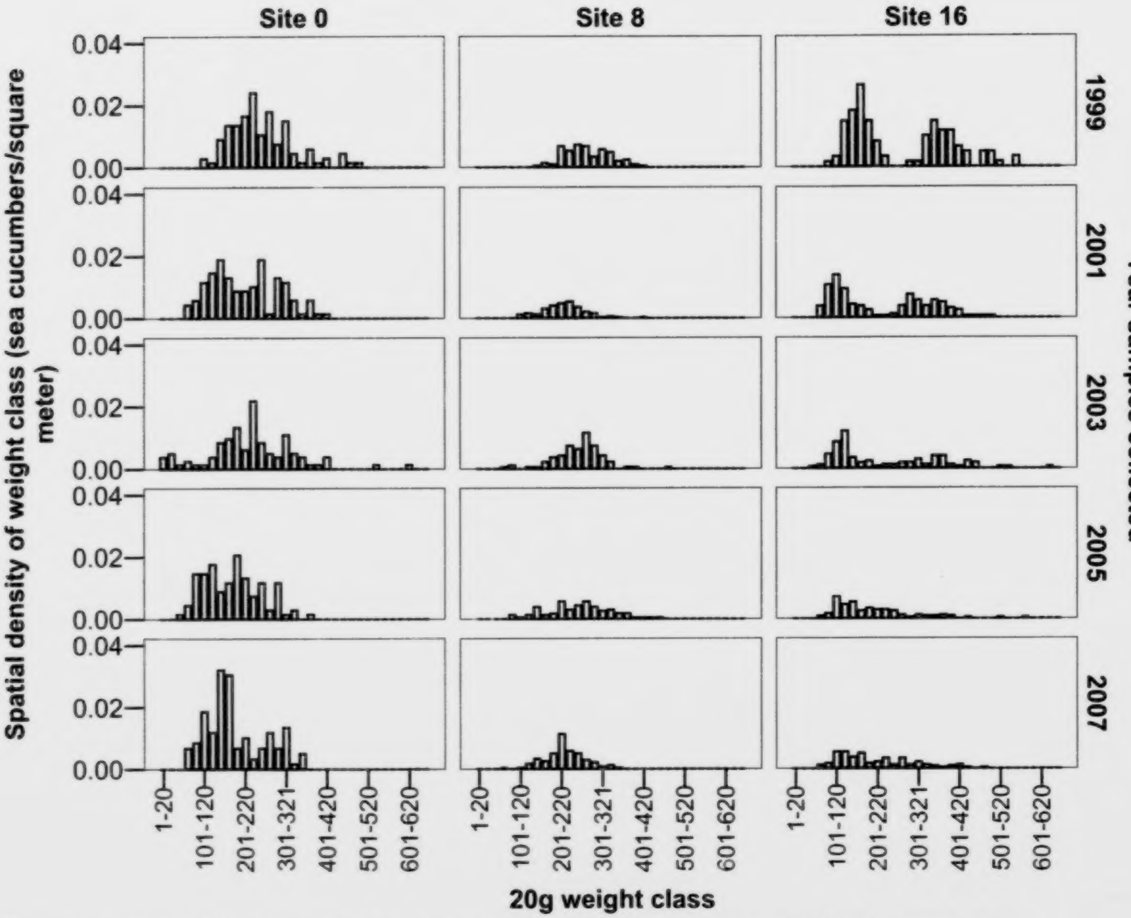


Figure 15c. Spatial density of 20 g weight classes of biosamples collected during surveys in the Jervis Inlet EFA.

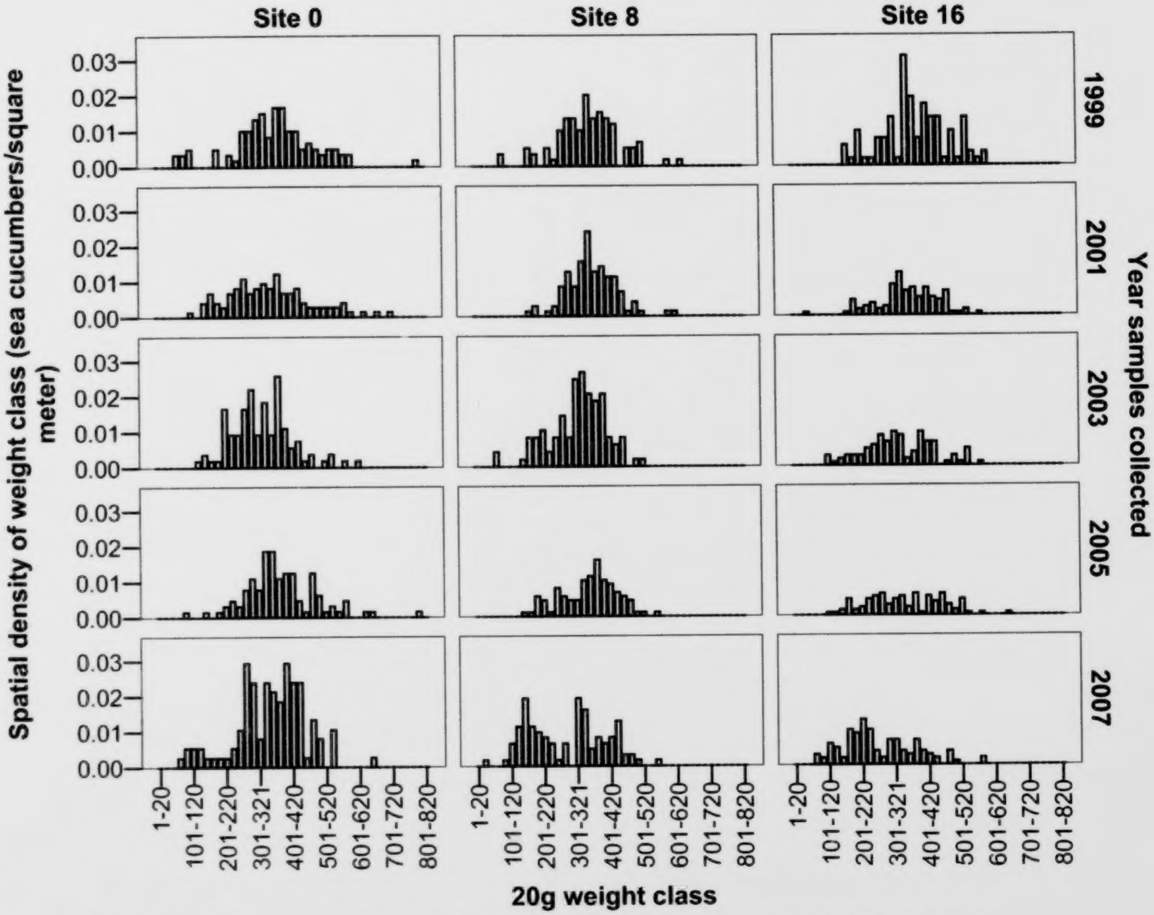


Figure 15d. Spatial density of 20 g weight classes of biosamples collected during surveys in the Zeballos EFA.

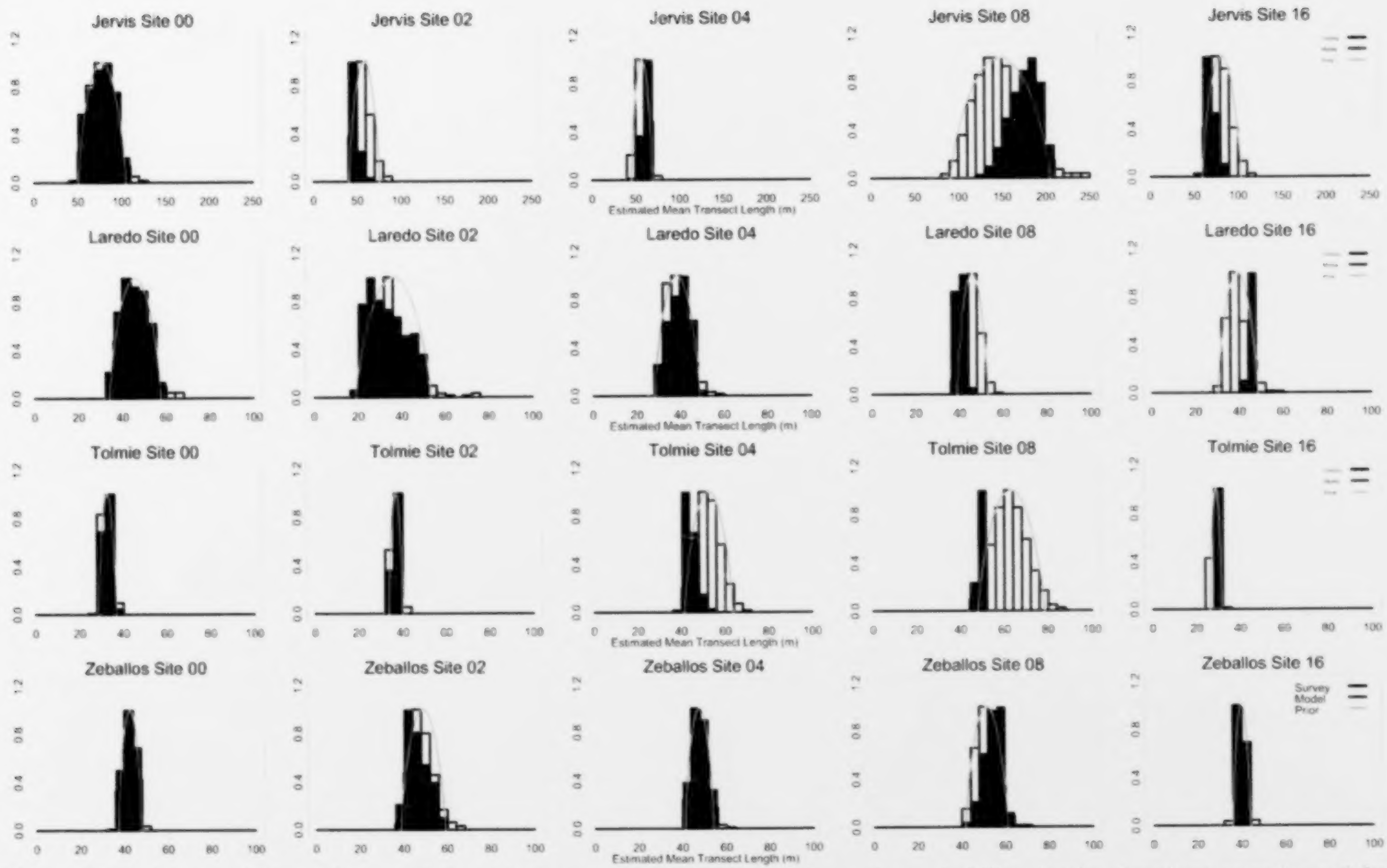


Figure 16. Estimates of Mean Transect Length in metres. The empty bars shows the probability density functions as estimated from bootstrapping and BCa methods. The orange curves are the prior-distributions used in the analyses. The green bars show the posterior distributions that resulted from the analyses.

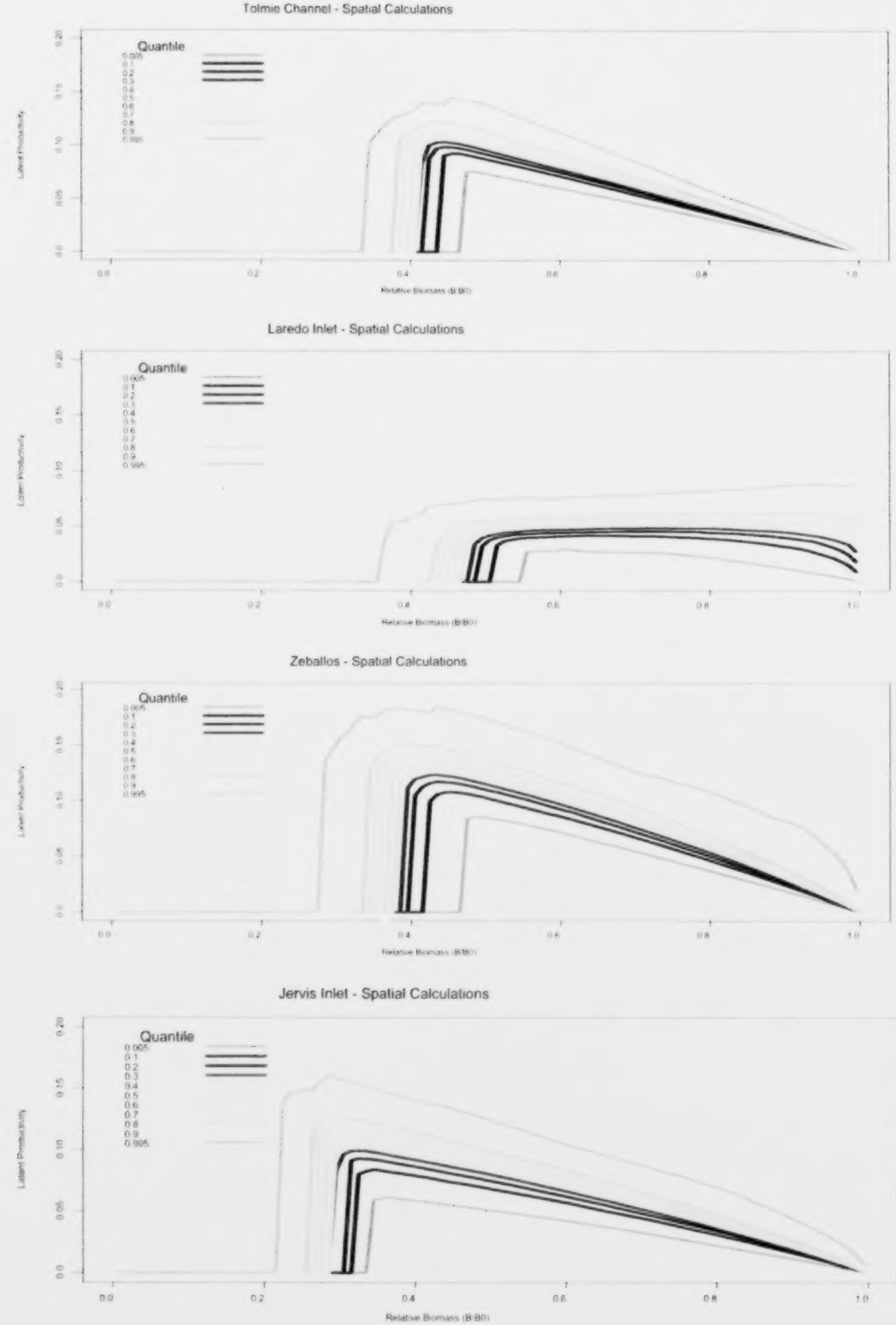


Figure 17. Truncated productivity curves for Tolmie, Laredo, Zeballos and Jervis EFAs. The sharp drop in the curve is the x-truncate value, which is the modelled median value of the relative population size one year prior to the most recent survey.

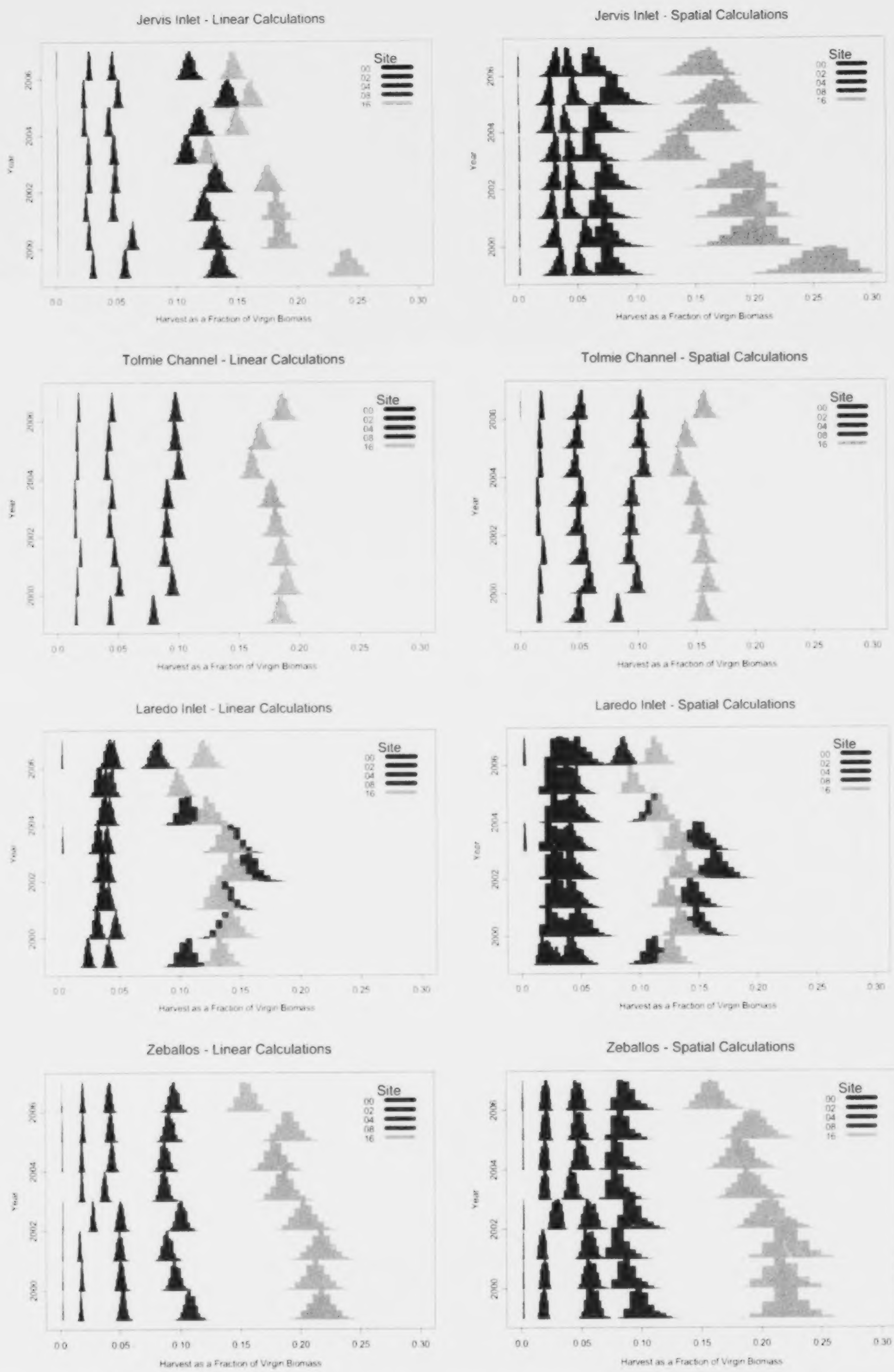
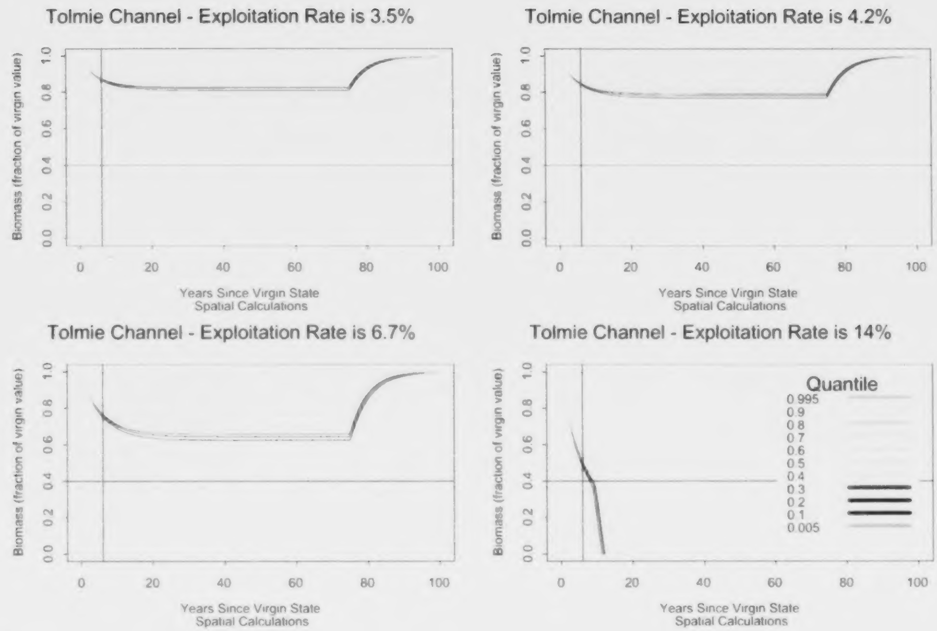


Figure 18. Harvest as a proportion of the virgin biomass in each of the four Experimental Fishery Area harvest sites.

A)



B)

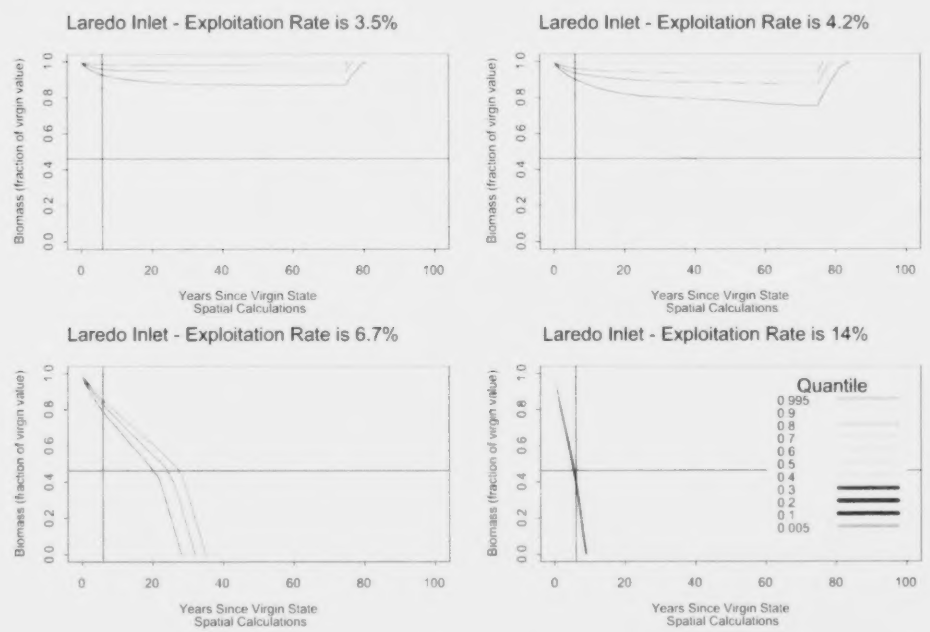
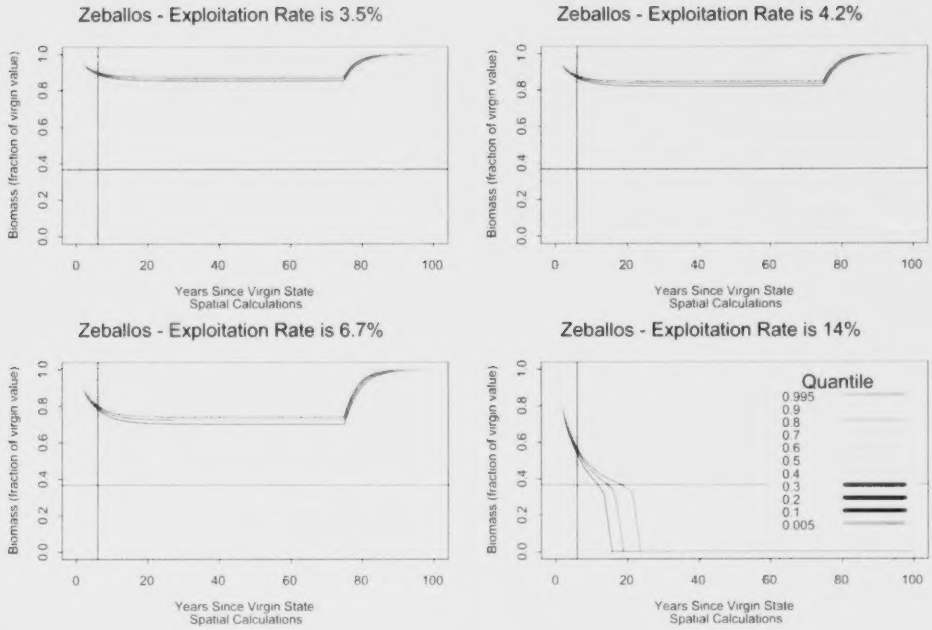


Figure 19. Simulated impacts of various levels of annual harvesting on *P. californicus* populations in A) Tolmie Channel, B) Laredo Inlet. The horizontal line is the median estimate of the lower range of experimental data ($x_{truncate}$), the vertical line is the year before the last survey and year zero corresponds to the survey conducted at the beginning of the experiment.

C)



D)

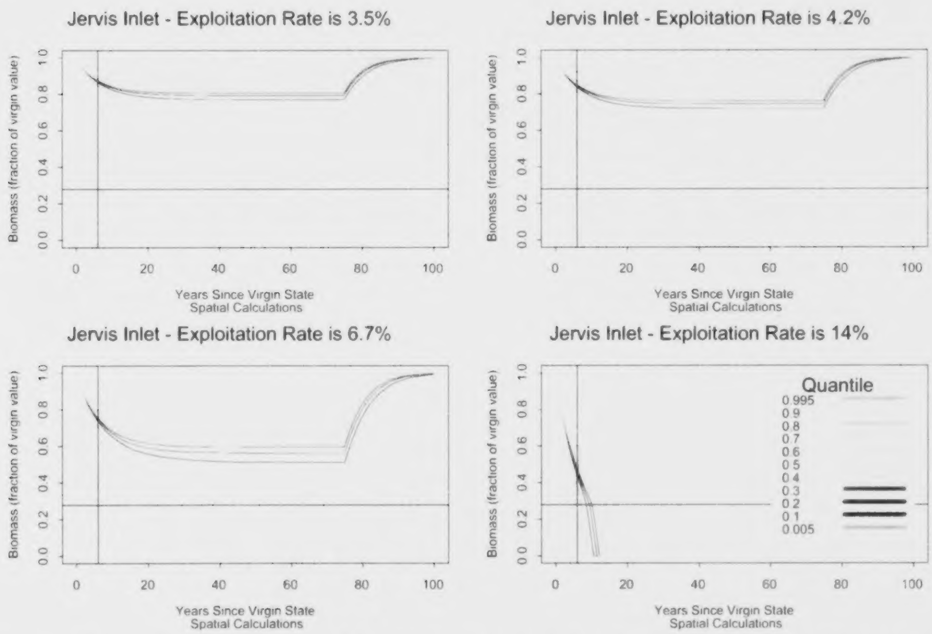


Figure 19, continued. Simulated impacts of various levels of annual harvesting on *P. californicus* populations in C) Zeballos Inlet and D) Jervis Inlet. The horizontal line is the median estimate of the lower range of experimental data ($x_{truncate}$), the vertical line is the year before the last survey and year zero corresponds to the survey conducted at the beginning of the experiment.

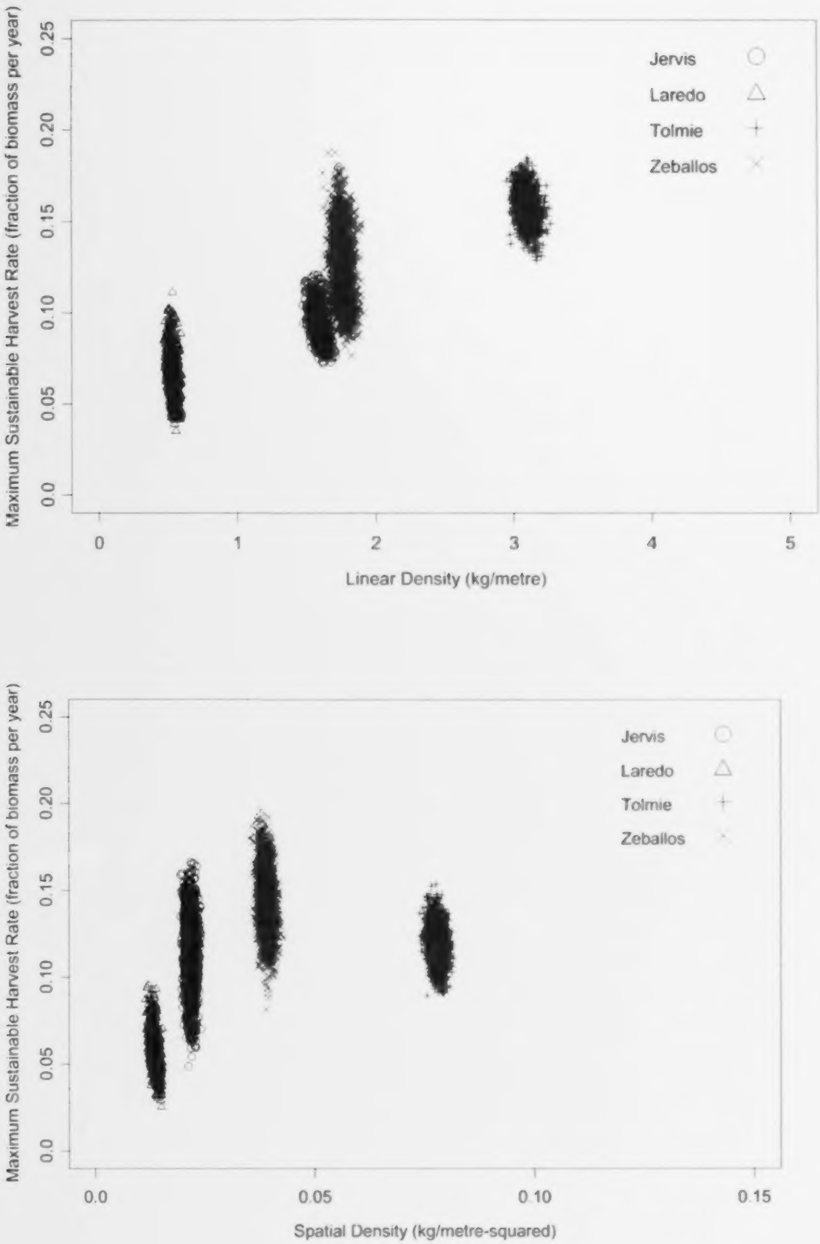


Figure 20. Maximum Sustainable Harvest Rate (MSHR) versus linear and spatial estimates of virgin biomass density. Each point within an EFA cloud corresponds to a step in a Monte Carlo Markov Chain.

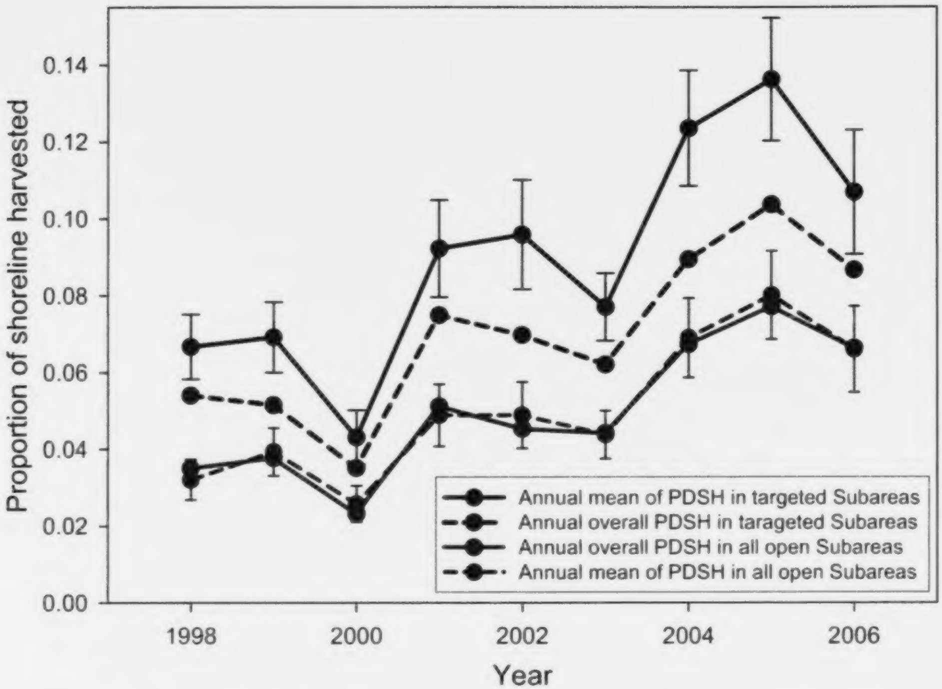


Figure 21. Proportion of dissolved shoreline harvested (*PDSH*) from 1998–2006. Error bars are +\- 1 standard deviation of the mean.

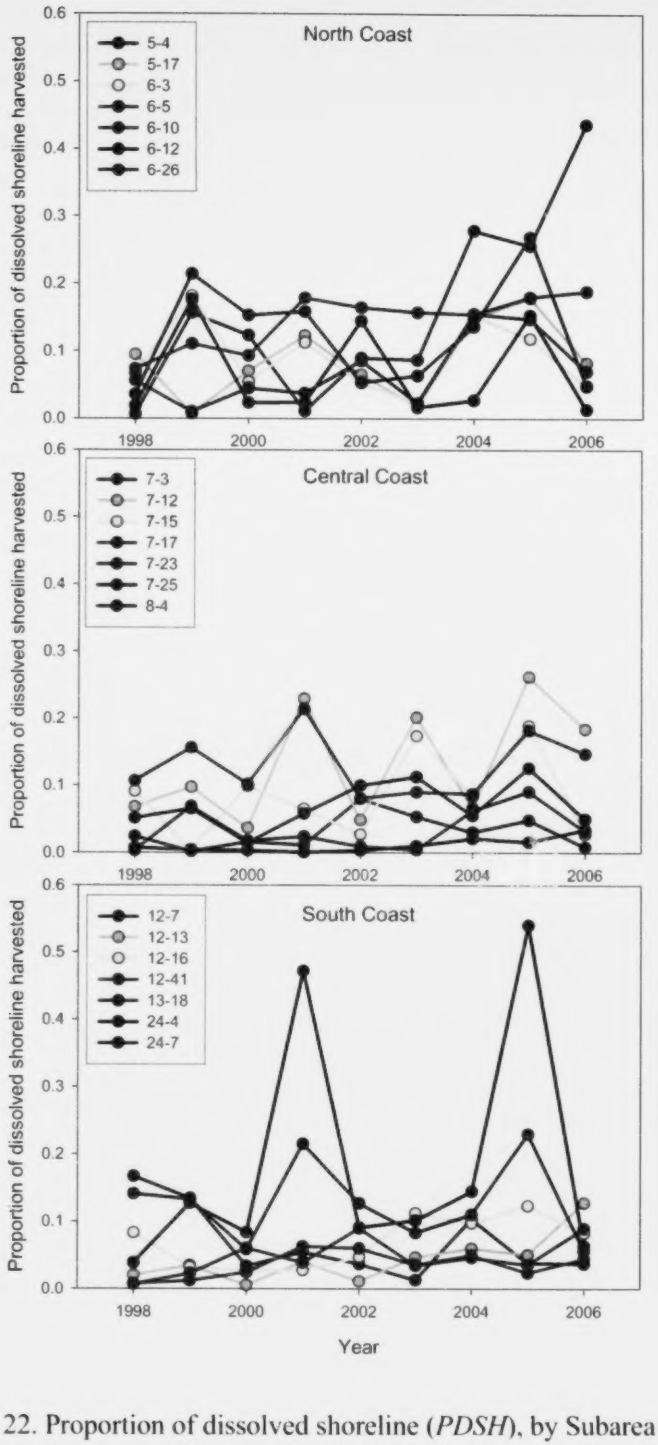


Figure 22. Proportion of dissolved shoreline (*PDSH*), by Subarea and Region, for the 21 Subareas where sea cucumbers were harvested every year from 1998–2006.

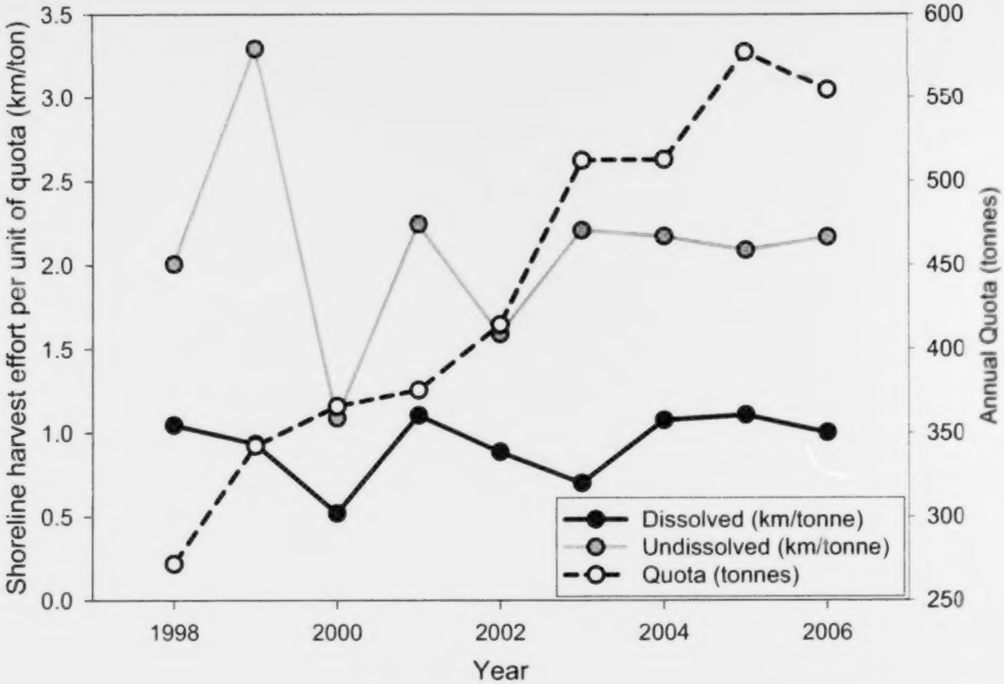


Figure 23. Ratio of total length of shoreline harvested to annual sea cucumber quota (km/t split weight) from 1998–2006.

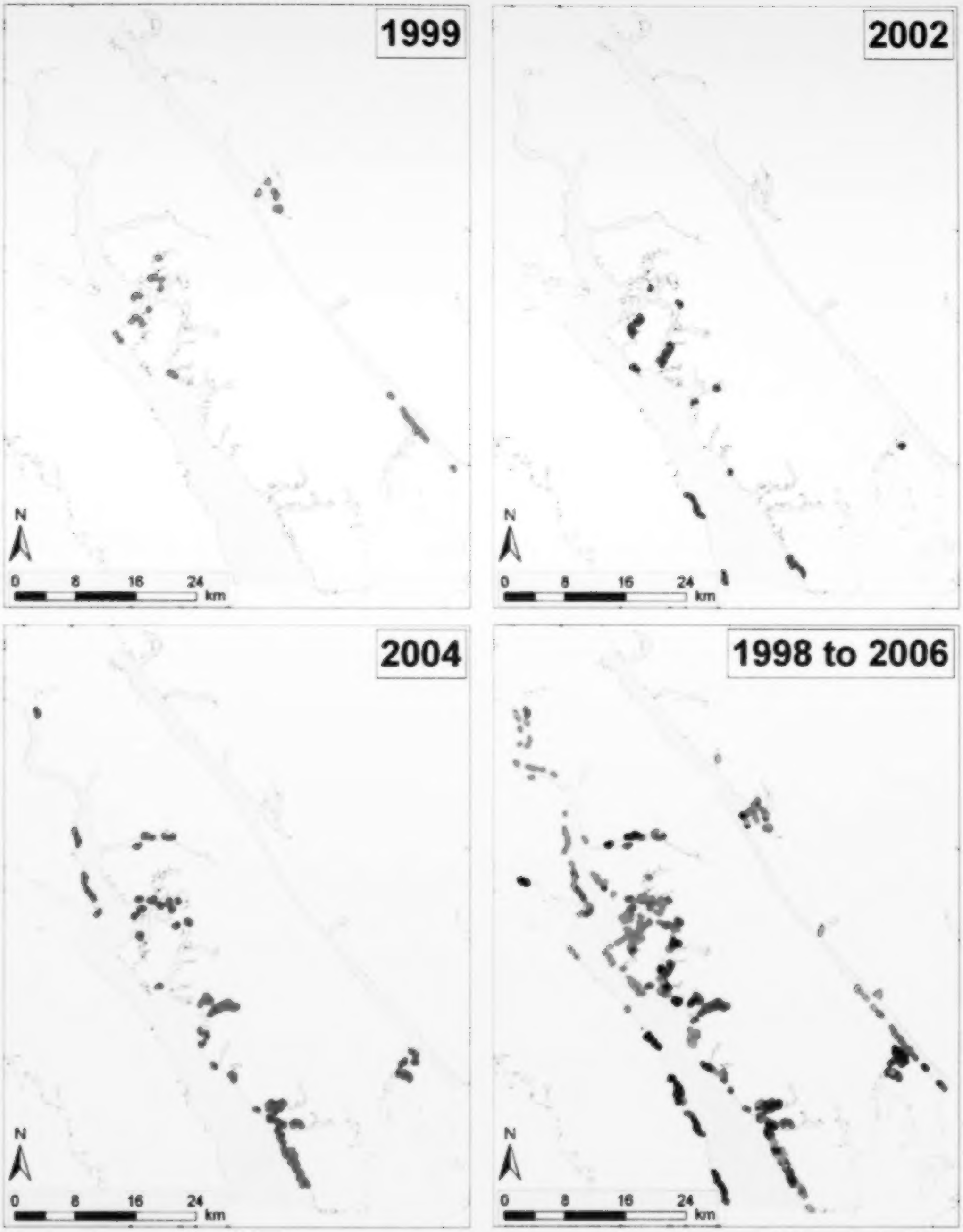


Figure 24. The location of fishing events, in the giant red sea cucumber fishery, for Quota Management Area 5B (shaded area) for 1999, 2002, 2004 (as examples - first three panels) and all years from 1998 to 2006 combined (last panel).

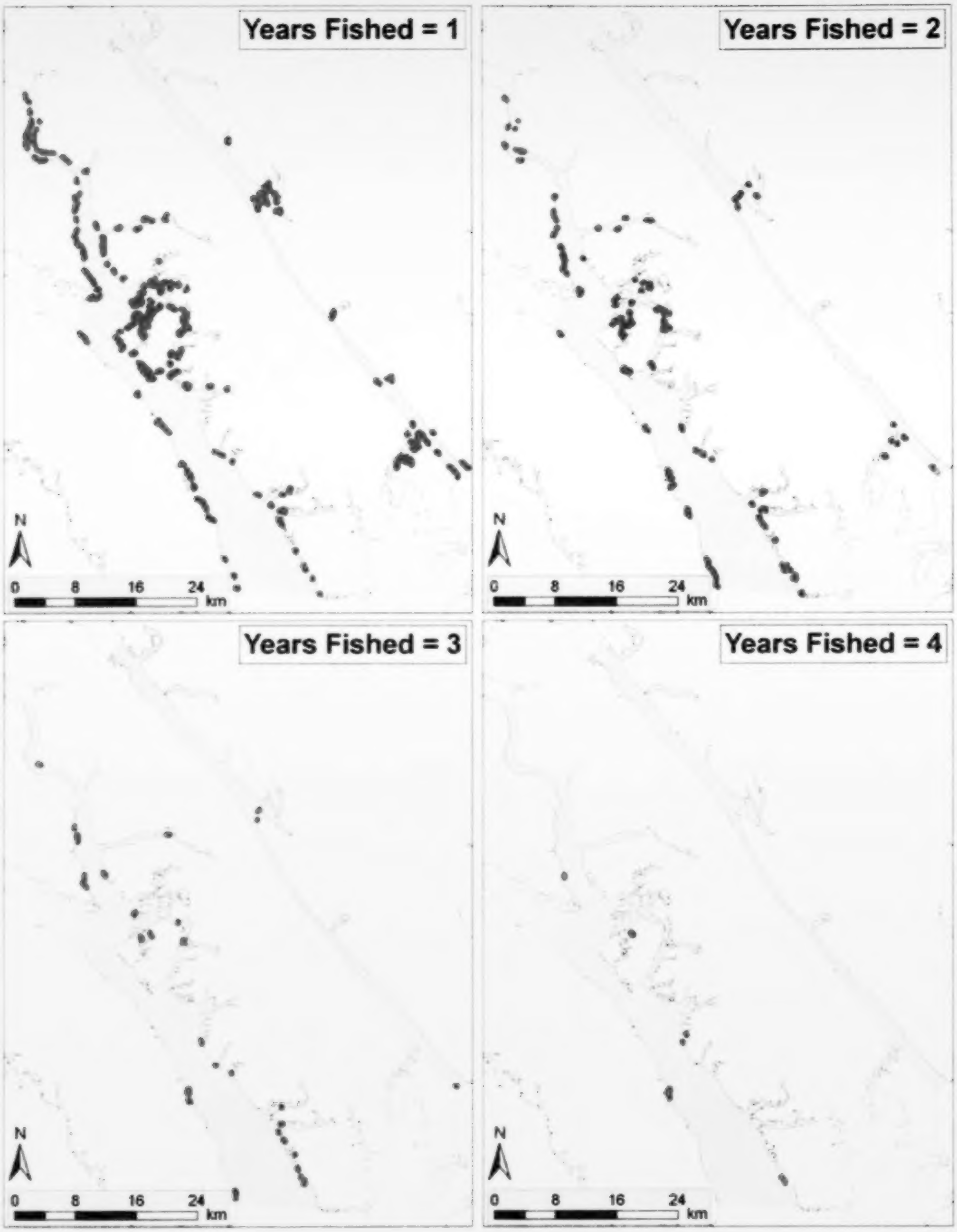


Figure 25. The location and number of years segments of shoreline in Quota Management Area 5B (shaded area) were fished, for giant red sea cucumbers, from 1998 to 2006. No segment of shoreline was targeted for fishing in 5, or more, years from 1998 to 2006.

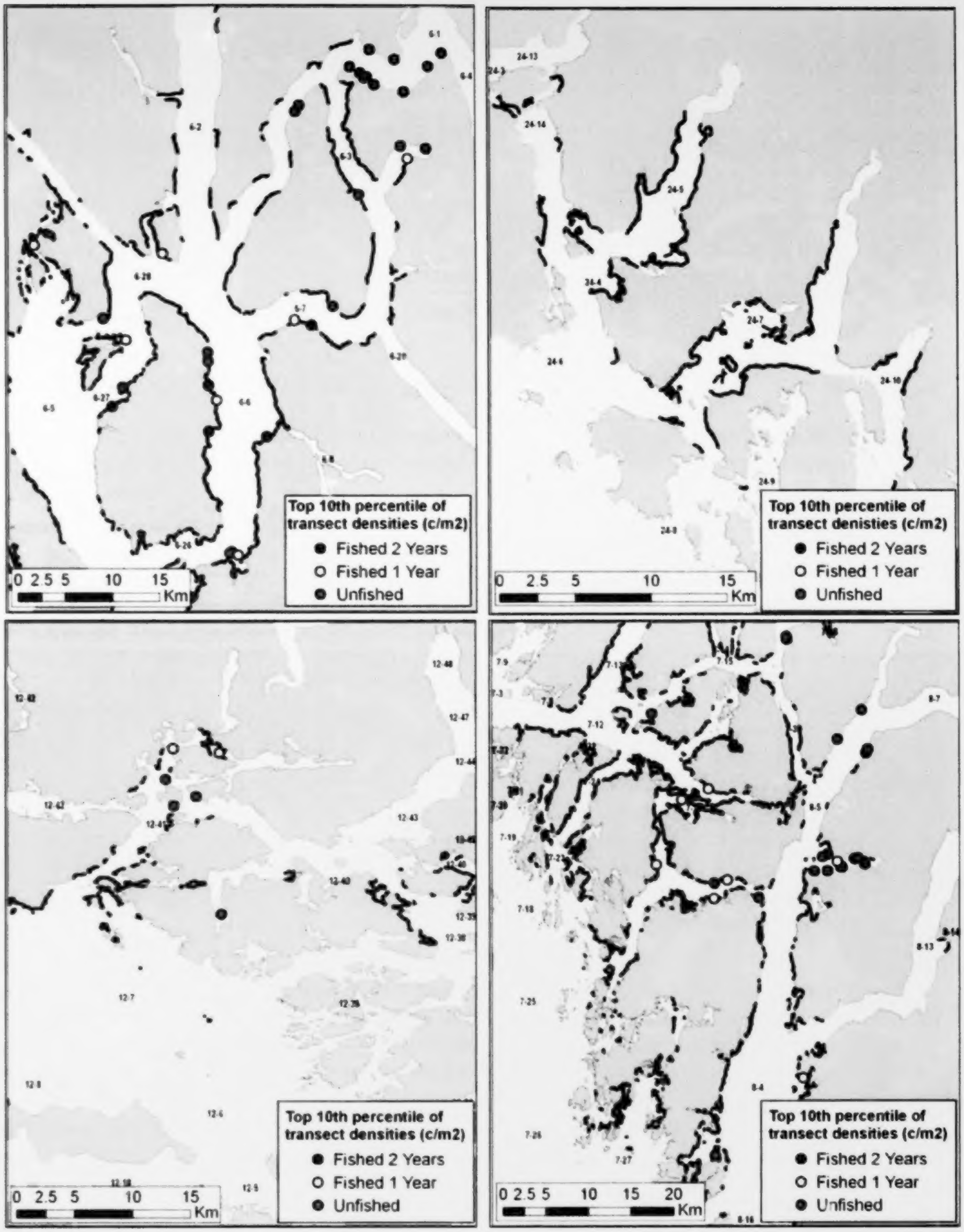


Figure 26. Locations of survey transects with densities in the top 10th percentile (higher than 0.47 cucumbers/m^2) of all recent (2004 to 2007) coast-wide survey transects. These transects, from 1998 to 2006, were either unfished (red circles), fished in one year only (yellow circles) or fished in two years (grey squares). The blue lines illustrate the shoreline that was harvested from 1998 to 2006.

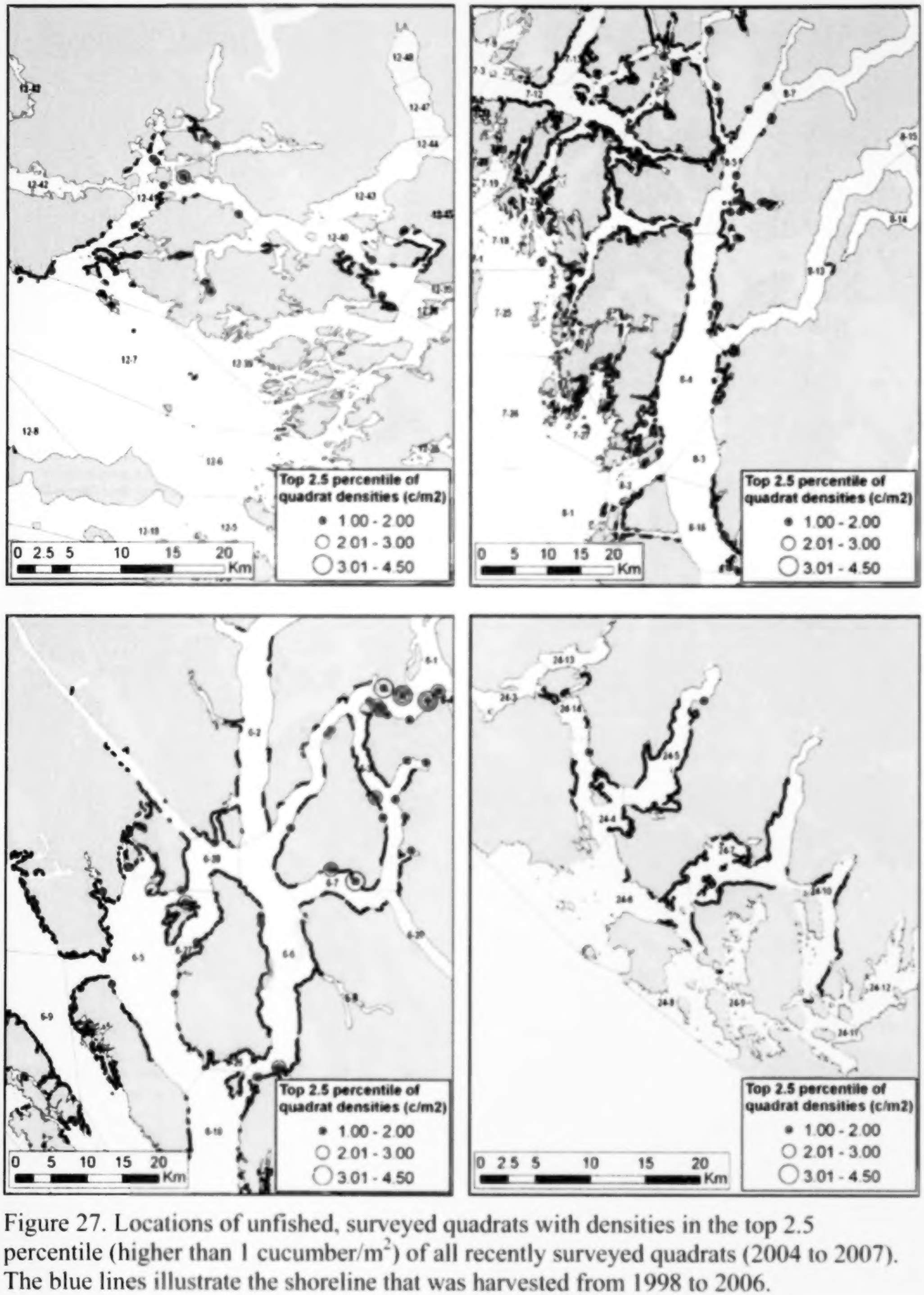


Figure 27. Locations of unfished, surveyed quadrats with densities in the top 2.5 percentile (higher than 1 cucumber/m^2) of all recently surveyed quadrats (2004 to 2007). The blue lines illustrate the shoreline that was harvested from 1998 to 2006.

11 Appendix 1. PSARC Invertebrate Subcommittee - Request for Working Paper

Date Submitted: March 17, 2006

Individual or group requesting advice:

- Juanita Rogers, Guy Parker, Rick Harbo (Fisheries and Aquaculture Management), Pacific Sea Cucumber Harvesters Association (PSCHA)

Proposed PSARC Presentation Date:

- Fall 2007

Subject of Paper (title if developed):

- Evaluation of commercial and experimental Sea Cucumber fisheries in BC during Phase 1 fishery development and recommendations for the Phase 2 fishery expansion.

Lead Author(s):

- Claudia Hand, Wayne Hajas, Janet Lochead, Nicholas Duprey and Julie Deault, Marine Ecosystems and Aquaculture Division

Fisheries Management Author/Reviewer:

- Pauline Ridings, Juanita Rogers, Rick Harbo (Fisheries and Aquaculture Management)

Background and Rationale for request:

- In 1997, the commercial sea cucumber fishery was shifted from a 2- and 3-year rotation to an annual fishery for the purpose of collecting a time-series of fishery data for use in biomass dynamic models. An adaptive management plan was adopted, where the commercial fishery was restricted to 25% of the BC coast, experimental fishing was allowed 25% of the coast and 50% of the coast was closed until information from research projects was sufficient to design an assessment framework for a sustainable fishery.

- DFO has worked with the PSCHA and First Nations since 1997 to develop stock assessment programs in an effort to increase the biological information available for sea cucumber stocks in BC. A description of the research programs forming the Phase 1 fishery was presented to PSARC in 1999. These programs included experimental fisheries to evaluate harvest rates, and broad-brush transect surveys in commercial areas to estimate density and biomass. Modified baseline density estimates derived from data collected from commercial area surveys was presented to PSARC in 2002.

- Commercial fishermen report that annual harvest is leading to a reduced animal size in some sea cucumber populations, with resulting marketing problems. The industry requests that alternate areas be opened and made available under the quota fishery in order to reduce the effort that is concentrated in some areas of the BC coast and allow recovery of the populations. Industry also requests a return to a rotational harvest strategy for sea cucumbers over the entire BC coast.

- Results of simulation modelling to evaluate rotational fisheries, along with results of preliminary analysis to look for evidence of decreasing size or density from research

data, was presented to PSARC in 2005. Deficiencies in market and biological samples were identified and as a result the analysis of these samples could not substantiate the fishermen's statements. Results from simulation modelling did suggest that rotational fisheries would result in larger animals and higher yield.

- Industry maintains that a rotational fishery would be beneficial to stocks by allowing them time to recovery, thereby producing larger animals. Managers are requesting a thorough review of commercial and experimental fishery information and survey results in order to evaluate the current management and assessment frameworks.

Objective of Working Paper:

To review and evaluate the commercial and experimental fishery data, survey data and biological data collected during Phase 1 of the fishery, discuss implications to stock sustainability and options that are available and recommend changes to the assessment framework for the existing fishery, if appropriate.

Question(s) to be addressed in the Working Paper:

What are the impacts of commercial harvest on sea cucumber populations?

What is the spatial distribution of commercial fishing effort over time? Are there concerns of serial stock depletion that would warrant area closures?

Has sufficient information been collected to recommend a sustainable harvest strategy in an expanded fishery (beyond the current 25% of the coast)? If not, what additional information is required? What is a conservative, sustainable annual harvest rate to be used in the commercial fishery?

What would constitute an effective scientific monitoring program in an expanded commercial area that would allow an assessment of impacts? For example, transect survey frequency and intensity, protocols for biological sampling.

Stakeholders Affected:

- Commercial, First Nations, recreational, or other interests

Timing Issues Related to When Advice is Necessary:

- Presentation in November 2007 will allow time for resource managers to draft and consult on change to the commercial harvest plan for October 2008.

Approval:

Head, Shellfish & Marine Mammals Assessment	Date
Regional Resource Manager – Invertebrates	Date

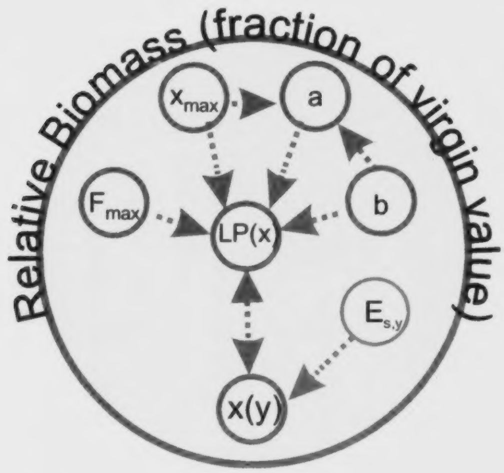
12 Appendix 2. Mean sea cucumber split weight, sample size and standard error by Experimental Fishing Area (EFA), site and year.

		Site 0			Site 2			Site 4			Site 8			Site 16		
EFA	Year	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE
Laredo Inlet	1998	45 (2)	242.9	9.35	(0)			100 (2)	245.3	5.76	50 (1)	304.7	10.46	100 (2)	253.5	6.67
	1999	**71 (2)**	**277.8**	**6.45**	**61 (2)**	**304.9**	**15.59**	**65 (2)**	**228.5**	**6.24**	**53 (2)**	**364.3**	**14.14**	**58 (2)**	**224.2**	**8.44**
	2000	59 (2)	296.5	9.37	64 (2)	310.4	15.07	61 (2)	245.2	5.75	116 (2)	300.3	9.27	65 (2)	282.2	7.43
	2001	**51 (2)**	**304.3**	**8.49**	**53 (2)**	**294.5**	**14.70**	**74 (2)**	**275.2**	**8.86**	**58 (2)**	**335.0**	**15.91**	**53 (1)**	**200.7**	**7.15**
	2002	50 (2)	324.6	15.60	50 (2)	298.3	14.07	51 (2)	254.2	7.27	51 (2)	365.7	15.14	50 (2)	270.5	12.19
	2003	**51 (2)**	**354.9**	**9.90**	**50 (2)**	**324.6**	**14.00**	**50 (2)**	**272.6**	**6.43**	**50 (2)**	**336.5**	**13.98**	**53 (2)**	**278.4**	**7.57**
	2004	50 (2)	298.6	9.44	50 (2)	315.8	11.02	50 (2)	283.7	6.41	49 (2)	337.7	16.15	50 (2)	284.2	10.44
	2005	**50 (2)**	**327.2**	**12.99**	**50 (2)**	**293.0**	**11.16**	**50 (2)**	**278.3**	**8.26**	**50 (2)**	**228.8**	**16.07**	**50 (2)**	**251.2**	**10.03**
	2006	50 (2)	345.4	15.36	50 (2)	344.3	15.41	50 (2)	337.3	9.60	49 (2)	339.2	16.44	50 (2)	316.2	10.52
	2007	**53 (2)**	**311.2**	**12.73**	**51 (2)**	**317.4**	**14.57**	**56 (2)**	**291.6**	**9.10**	**49 (2)**	**215.0**	**14.72**	**53 (2)**	**258.0**	**11.86**
Tolmie Channel	1998	94 (2)	224.7	6.31	73 (2)	277.5	10.93	100 (2)	296.3	7.55	100 (2)	321.7	8.06	97 (2)	235.0	5.69
	1999	**97 (2)**	**229.9**	**7.42**	**96 (2)**	**294.5**	**10.40**	**92 (2)**	**294.8**	**10.64**	**88 (2)**	**339.1**	**8.39**	**99 (2)**	**210.8**	**6.05**
	2000	103 (2)	226.1	6.83	108 (2)	273.2	7.87	104 (2)	284.7	7.89	104 (2)	294.3	8.02	102 (2)	167.4	5.92
	2001	**103 (2)**	**246.6**	**6.37**	**101 (2)**	**247.1**	**7.08**	**100 (2)**	**279.7**	**7.96**	**99 (2)**	**302.1**	**7.17**	**98 (2)**	**176.9**	**5.33**
	2002	104 (2)	235.9	5.50	103 (2)	253.8	7.01	101 (2)	267.1	6.66	100 (2)	323.9	8.43	104 (2)	184.2	6.25
	2003	**102 (2)**	**220.9**	**5.09**	**102 (2)**	**222.2**	**6.42**	**105 (2)**	**311.2**	**7.29**	**102 (2)**	**278.5**	**7.31**	**106 (2)**	**197.7**	**6.06**
	2004	100 (2)	205.8	5.54	100 (2)	248.4	7.16	100 (2)	308.5	8.43	100 (2)	295.1	9.27	100 (2)	195.1	5.51
	2005	**100 (2)**	**217.7**	**5.90**	**100 (2)**	**272.7**	**8.71**	**100 (2)**	**272.9**	**8.72**	**100 (2)**	**337.8**	**8.27**	**100 (2)**	**175.4**	**6.90**
	2006	100 (2)	296.1	7.12	100 (2)	345.4	8.24	99 (2)	414.9	9.00	99 (2)	418.0	10.99	100 (2)	254.3	8.81
	2007	**101 (2)**	**229.5**	**7.32**	**107 (2)**	**275.6**	**7.24**	**100 (2)**	**332.9**	**9.91**	**99 (2)**	**329.9**	**11.47**	**101 (2)**	**179.5**	**6.47**
Jervis Inlet	**1999**	**104 (2)**	**254.4**	**7.93**	**106 (2)**	**217.2**	**7.52**	**110 (2)**	**231.6**	**6.87**	**101 (2)**	**273.4**	**5.51**	**102 (2)**	**270.7**	**12.24**
	2000	102 (2)	228.3	7.43	111 (2)	216.2	7.05	103 (2)	238.5	6.01	102 (2)	258.3	5.75	104 (2)	222.1	10.34
	2001	**108 (2)**	**212.4**	**7.94**	**105 (2)**	**189.7**	**6.11**	**102 (2)**	**204.9**	**5.35**	**118 (2)**	**220.1**	**6.39**	**144 (2)**	**220.0**	**9.64**
	2002	103 (2)	214.2	7.54	107 (2)	206.2	7.59	101 (2)	207.7	7.01	100 (2)	207.4	5.70	112 (2)	229.0	10.91
	2003	**101 (2)**	**224.4**	**10.36**	**102 (2)**	**184.1**	**6.37**	**103 (2)**	**210.7**	**10.90**	**101 (2)**	**252.3**	**5.85**	**105 (2)**	**224.3**	**12.67**
	2004	99 (2)	192.0	7.84	101 (2)	178.3	5.89	103 (2)	179.0	7.39	101 (2)	240.6	6.87	94 (2)	201.1	12.00
	2005	**100 (2)**	**179.9**	**6.95**	**100 (2)**	**203.8**	**6.24**	**100 (2)**	**178.5**	**6.80**	**100 (2)**	**251.0**	**7.72**	**100 (2)**	**196.1**	**9.61**
	2006	100 (2)	164.6	6.91	100 (2)	155.4	5.75	100 (2)	166.3	6.27	100 (1)	248.0	10.21	100 (2)	195.3	9.31
	2007	**103 (2)**	**187.0**	**7.22**	**100 (2)**	**191.6**	**5.34**	**100 (2)**	**182.5**	**6.52**	**103 (2)**	**218.8**	**5.01**	**103 (2)**	**204.6**	**9.16**
Zeballos	**1999**	**102 (2)**	**365.0**	**12.20**	**51 (1)**	**458.6**	**12.76**	**103 (2)**	**392.5**	**8.64**	**95 (2)**	**353.3**	**9.70**	**99 (2)**	**381.8**	**9.91**
	2000	69 (2)	369.3	21.42	57 (2)	393.6	15.22	112 (2)	401.1	10.52	100 (2)	348.4	7.00	99 (2)	374.7	10.85
	2001	**102 (2)**	**349.5**	**12.25**	**100 (2)**	**399.9**	**11.61**	**98 (2)**	**413.3**	**10.02**	**102 (2)**	**362.5**	**7.39**	**101 (2)**	**354.7**	**9.01**
	2002	103 (2)	346.2	10.38	101 (2)	357.2	11.09	101 (2)	367.1	9.49	105 (2)	343.9	9.46	102 (2)	335.9	10.27
	2003	**100 (2)**	**322.3**	**8.92**	**104 (2)**	**314.4**	**8.84**	**100 (2)**	**333.8**	**13.72**	**100 (2)**	**318.2**	**8.48**	**102 (2)**	**326.8**	**10.25**
	2004	100 (2)	366.7	8.63	52 (2)	308.3	12.00	100 (2)	325.6	10.78	100 (2)	342.3	9.79	100 (2)	349.6	13.67
	2005	**100 (2)**	**375.9**	**10.78**	**100 (2)**	**381.9**	**10.40**	**100 (2)**	**363.7**	**12.50**	**100 (2)**	**344.7**	**8.35**	**100 (2)**	**340.0**	**11.34**
	2006	100 (2)	330.4	12.18	100 (2)	289.5	12.98	100 (2)	286.6	12.10	100 (2)	322.9	9.90	100 (2)	285.7	11.00
	2007	**107 (2)**	**342.5**	**10.28**	**106 (2)**	**287.4**	**11.82**	**103 (2)**	**308.8**	**13.51**	**105 (2)**	**274.0**	**11.26**	**110 (2)**	**258.4**	**10.55**

13 Appendix 3: Directed Acylic Graph (DAG) for the combined model

Directed acyclic graphs (DAG) are common tools for representing models in Bayesian analyses (Gilks et al. 1996). Due to the size and complexity of the model, the DAG was separated into components and thereby deviates somewhat from the usual conventions.

Below is a directed acyclic graph (DAG) representation of the productivity model.

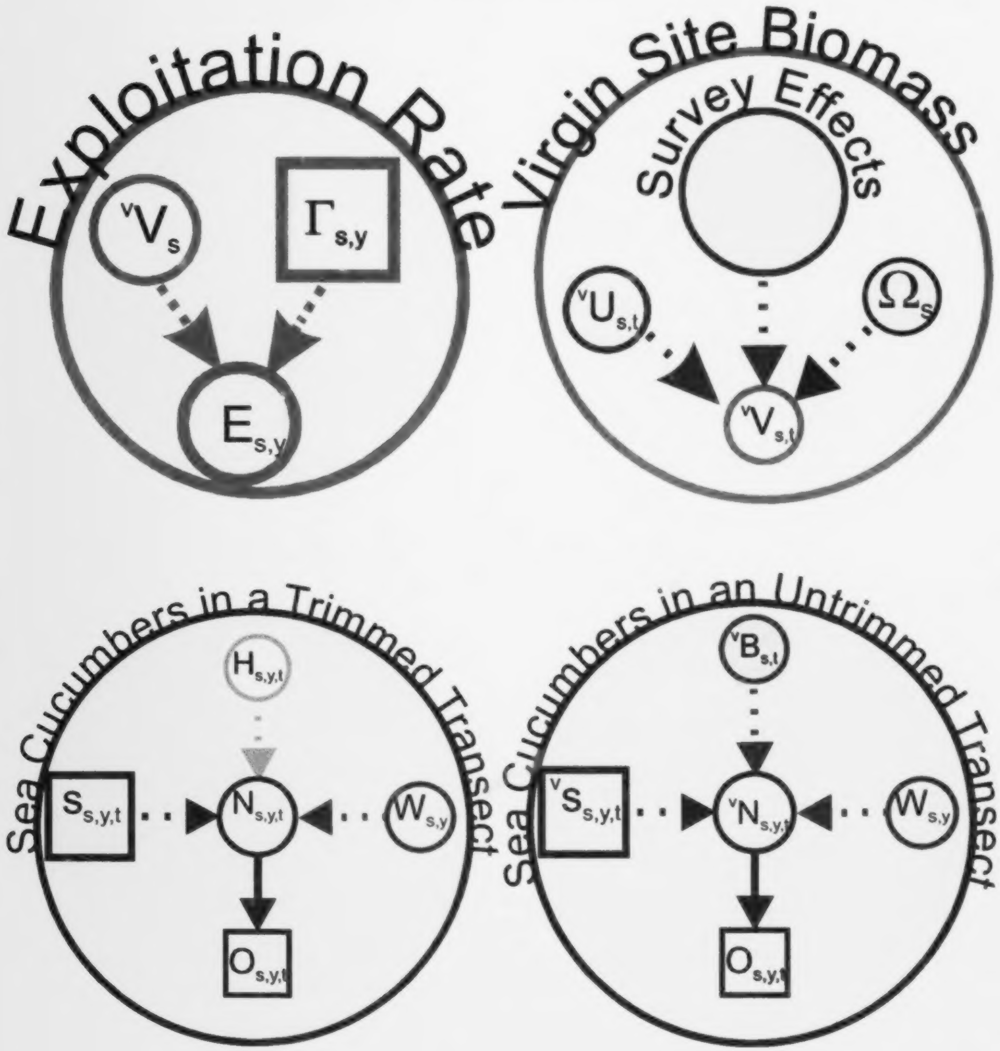


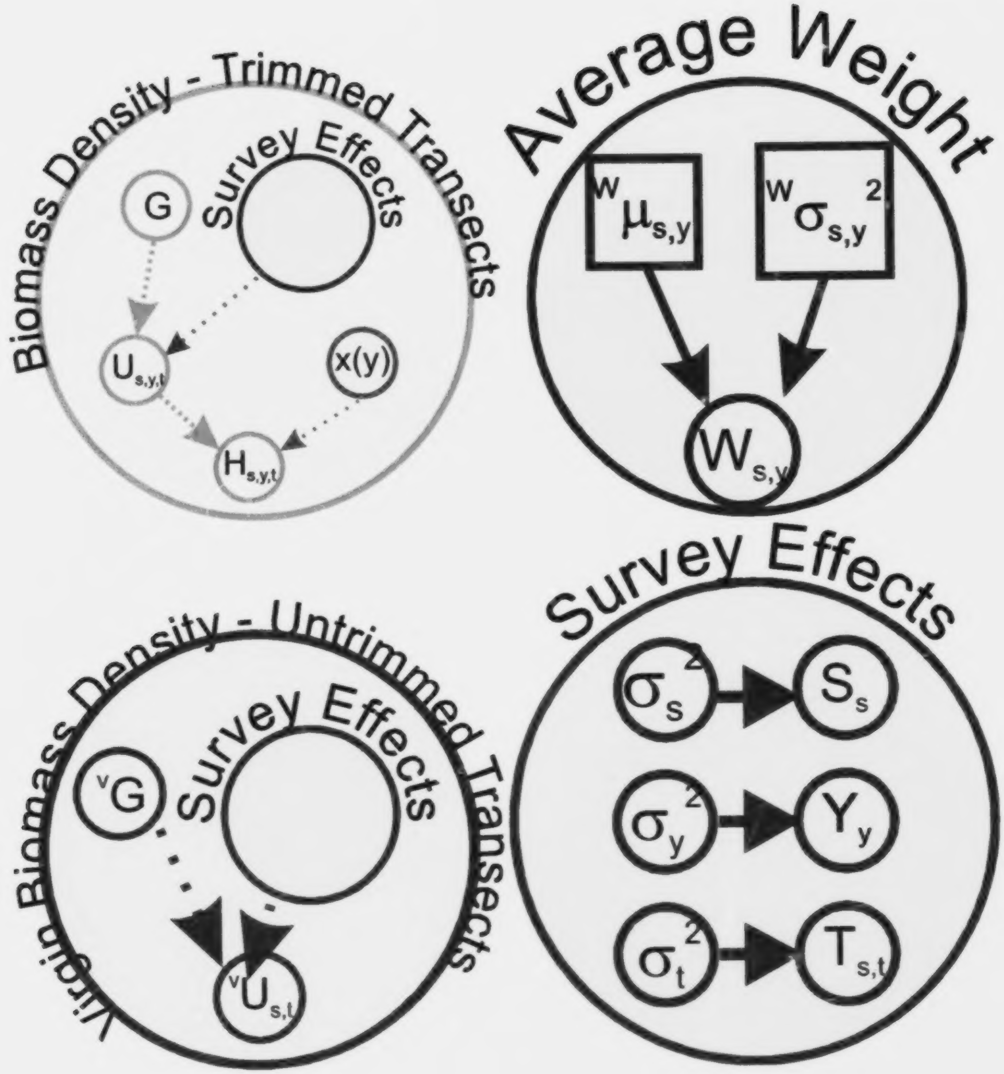
The DAG shows the flow of information in the model. Circles represent probabilistic nodes and squares represent observable data.

These are the ways that the DAG deviates from the usual conventions:

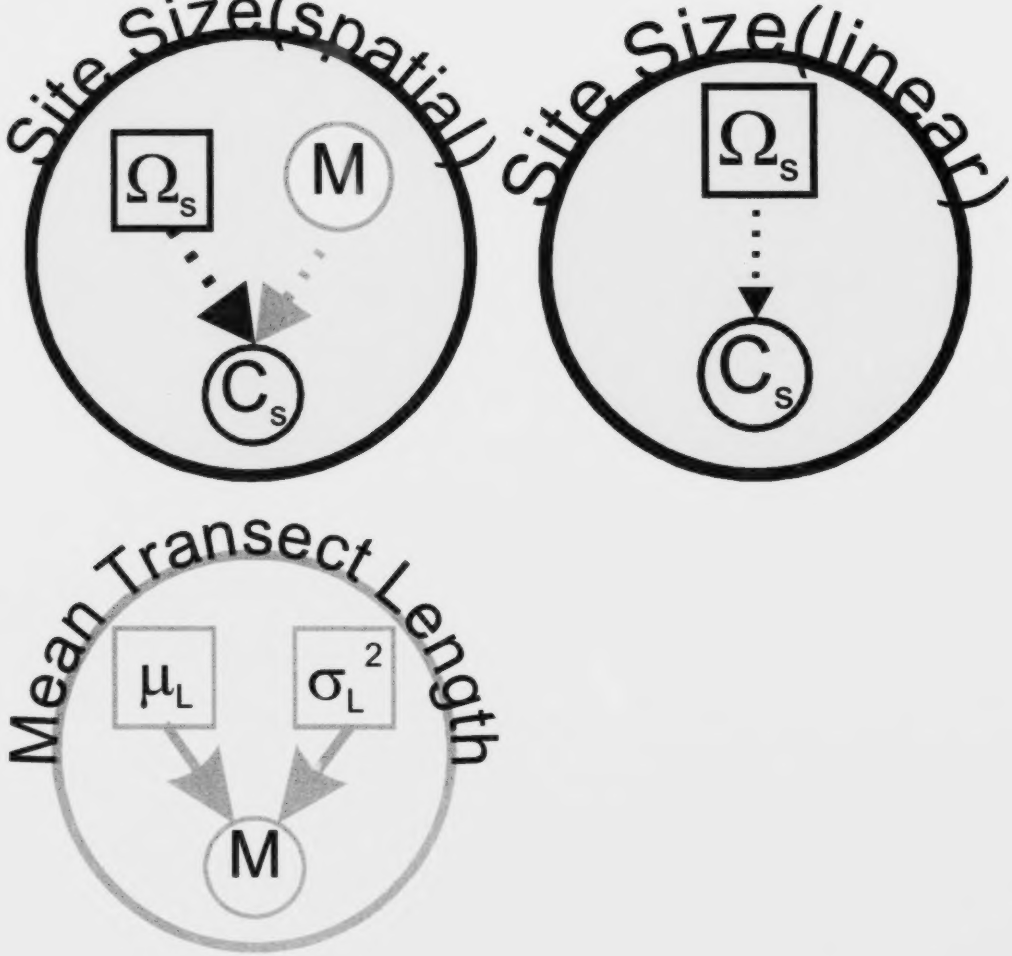
- It only shows part of the model. The model has been distributed among multiple DAGs in order to improve readability. DAGs for the rest of the model are shown in other figures.
- The DAG is colour-coded. Most notably, $E_{s,y}$ is a different colour than the rest of this particular DAG. Parent nodes of $E_{s,y}$ are shown in other components of the DAG.
- The DAG terminates at a probabilistic node, x(y). This node also appears as a parent-node in DAGs representing different parts of the model. A node appears in the same colour each time it is used.
- The DAG represents the flow of information for performing calculations as opposed to the flow of causality. There is one instance where this is significant. There is a two-headed arrow between $LP(x)$ and x(y) representing the numerical solution to a differential equation. However, x(y) is fully defined given $LP(x)$ and $E_{s,y}$. Therefore in a causal sense, the system is acylic.

The rest of the model is represented in the DAGs below. It should be noted that in order to further simplify the DAG, survey effects have been combined into a single node.





Biomass Density - Trimmed Transects
Survey Effects
G
$U_{s,y,t}$
x(y)
$H_{s,y,t}$
Average Weight
$^{w}\mu_{s,y}$
$^{w}\sigma_{s,y}^{2}$
$W_{s,y}$
Virgin Biomass Density - Untrimmed Transects
Survey Effects
^{v}G
$^{v}U_{s,t}$
Survey Effects
σ_s^2
S_s
σ_y^2
Y_y
σ_t^2
$T_{s,t}$



References:

- Gilks W.R., Richardson S. and Spiegelhalter D.J. "Markov Chain Monte Carlo in Practice". *Chapman & Hall/CRC*, 1996.